



Hydraulic Modeling of Chicago Area Waterways System (CAWS) to Assess the Impact of Hydrologic Separation on Water Levels and Potential Flooding during Extreme Rainfall Events in Chicago, Illinois

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Executive Summary

Purpose and Scope

In the Chicago Area Waterways (CAWS) drainage area, there are 255 Combined Sewer Outfalls (CSO) owned by the City of Chicago, the Metropolitan Water Reclamation District of Greater Chicago (MWRDGC), and surrounding municipalities. Chicago-area CSOs discharging to the CAWS currently drain away from Lake Michigan during most wet weather conditions. Consequently, the majority of CSO events in the Chicago metropolitan area do not affect Lake Michigan. However, the gates at the waterway controlling works that separate the Chicago-area waters and Lake Michigan are opened during certain heavy rainfall events in order to prevent local flooding.

At the same time, there is a growing interest in controlling the potential migration of invasive species towards the Great Lakes. Hydrologic separation of the Great Lakes from the Mississippi River watershed is being considered as an alternative to prevent the migration of invasive species. Such separation by means of barriers in the waterways implies that the urban drainage system will have to operate under a very different set of conditions so having a model for the whole system could prove very useful. The University of Illinois has worked towards the development of an urban hydrologic model for Chicago.

Physical separation of the Great Lakes and Mississippi River Basin to prevent the movement of aquatic invasive species (AIS), particularly Asian Carp, consists in the conveyance of water towards Lake Michigan by means of physical (solid) barriers at specific points along the CAWS. Regardless of the number of barriers and their location, this alternative constitutes a major intervention to the system, which will have an important impact on drainage, flooding, water quality and transportation in the Chicago area.

This work focuses on evaluating the impact of physical barriers on the hydraulic performance of the CAWS during extreme rainfall events. The assessment will be based on a 1D numerical model of the entire CAWS using the package HEC-RAS.

The main objective is the estimation of the hydraulic capacity of the CAWS (Figure E1) to convey the storm water runoff and combined sewer overflows (CSO) resulting from extreme rainfall events having different intensity, durations and frequencies. We would like to determine the impact of different extreme rainfall events (100-yr and 500-yr return periods) on the hydraulic performance of the CAWS, in the presence of different physical barriers along the South Branch of the Chicago River and the Calumet River. In particular, the September 13-15, 2008 storm event which resulted in +5 inches of rain in 24 hours (100-yr return period). This storm also indicates that the impact of antecedent conditions and back to back storms should be accounted for in the analysis of separation scenarios. The second storm event is represented by a synthetic hyetograph of 24 hours and 500-year return period, and equivalent hydrographs for tributaries for purpose of modeling in CAWS.

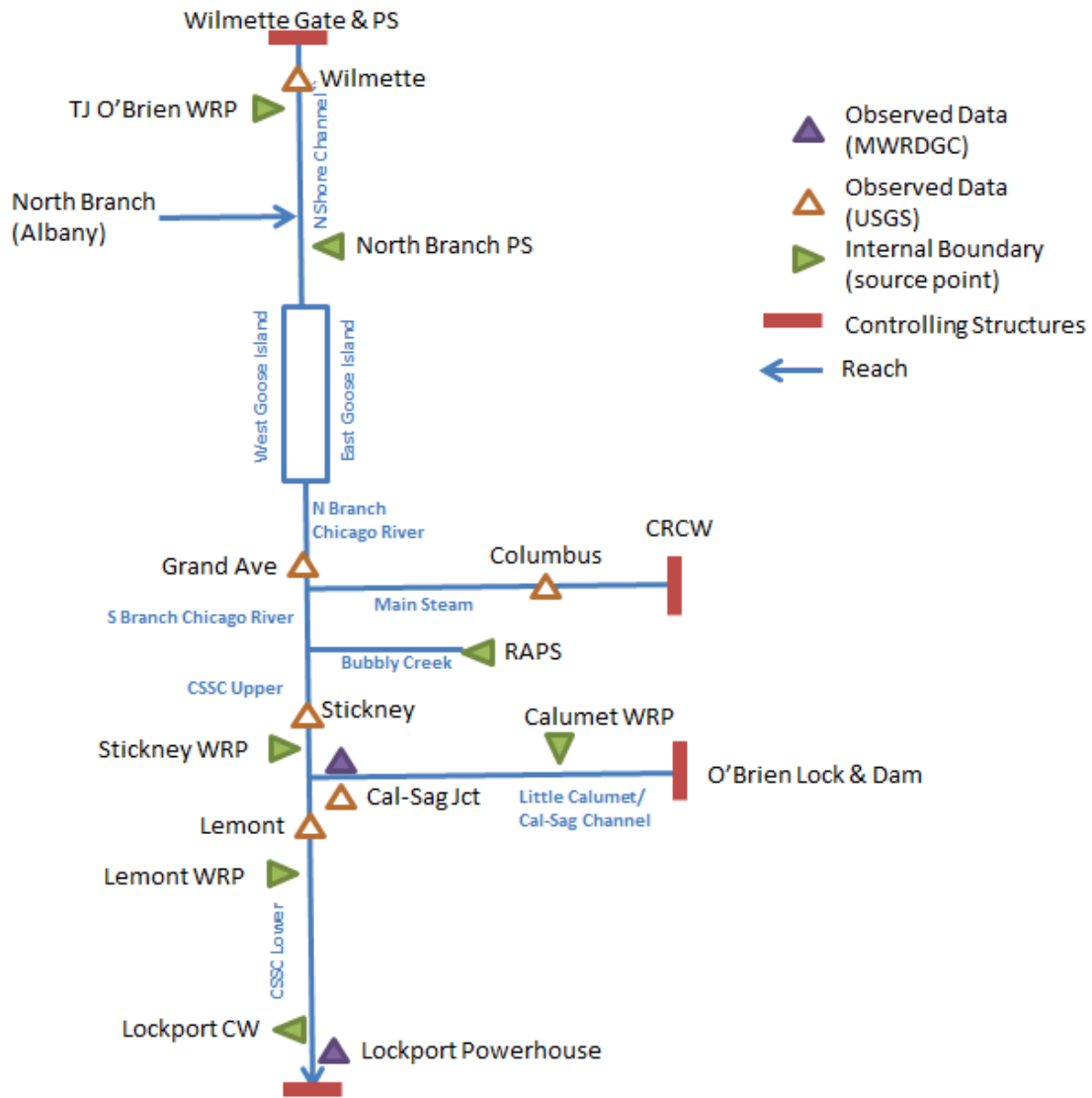


Figure E1: Schematic of Chicago Area Waterways System (HEC-RAS Model domain)

Methods and Scenarios

The unsteady HEC-RAS model (1D) developed by the US Army Corps of Engineers (Brunner, 2010) was set up for the hydraulic analysis of the CAWS. The computational domain consists of the North Shore Channel (NSC) from Wilmette, North Branch of the Chicago River (North Branch), Mainstem Chicago River, South Branch Chicago River, Bubbly Creek, Chicago Sanitary and Ship Canal (CSSC) down to the Lockport powerhouse, Cal-Sag Channel, and Calumet River. The controlling works at the lakefront (Wilmette, Chicago River Controlling Works (CRCW), O'Brien Lock & Dam) and Lockport (powerhouse and Controlling Works) were included. Short reaches of Upper North Branch Chicago River (upstream of the dam), and Little Calumet were also included in domain.

The model is not calibrated due to lack of data, in particular with respect to the discharge capacity of the controlling works, and flow discharges resulting from CSOs. Nevertheless it provides a better insight on the global behavior of the CAWS during severe precipitation events in the presence of the barriers.

Hydrologic events

Two storms for different hydrological events were considered in this study:

- September 13-15, 2008 storm event which resulted in +5 inches of rain in 24 hours (100-yr return period). This storm also indicates that the impact of antecedent conditions and back to back storms should be accounted for in the analysis of separation scenarios.
- Synthetic hyetograph of 24 hours and 500-years, and equivalent hydrographs for tributaries for purpose of modeling in CAWS.

These precipitation events were used in order to estimate CSO hydrographs in the City of Chicago. CSO discharges were estimated using the "City Model" and CS-TARP. The "City Model" is an InfoWorks sewer model developed for the City of Chicago and performs rainfall-runoff computations and sewer routing to TARP collecting structures. In this manner it was possible to obtain an estimate of the time distribution of CSOs discharged into CAWS.

TARP

Two TARP conditions were assumed. The first, referred as Finite-TARP, assumes that the storage volume of TARP is unavailable because it was filled up by a previous storm. This is a conservative scenario for flooding analysis. The second condition (Infinite-TARP) is for the fully open and operative TARP system completely empty when the storm hits. In that case it is assumed that any CSOs that are produced are a result of bottlenecks in the sewer pipe network rather than TARP shortage.

Lake Michigan

The level at Lake Michigan was another factor to be considered in this study. It is determinant of the conveyance capacity of the controlling structures and water levels in CAWS when lakefront gates are open. Lake levels of 0 CCD and +3 CCD were evaluated. These values are close to historic mean and maximum lake levels in the last 60 years, respectively.

Operation of controlling works

The operation of controlling works on the lake front boundaries of CAWS (Wilmette, CRCW, and O'Brien Lock & Dam) and at Lockport were based on the Dispatcher Manual 2013 by MWRDGC for flood control during wet weather. However, some changes on these rules were agreed upon with the GLC team for the modeling scenarios.

For the scenarios With Barrier the lakefront gates were fully open during the entire simulation period. On the scenarios Without Barriers, the criteria for gate opening are as stated in MWRDGC Dispatcher Manual (2013); with the condition that once opened they are not closed again.

The operation of sluice gates at Lockport Powerhouse (LPPH) and Controlling Works (LPCW) was based on MWRDGC Dispatcher Manual 2013 as well. However, for some scenarios the operation of turbines was defined as a fixed discharge leaving the system (2500 cfs) for sake of model stability. The operation in scenarios AE002, and AE004 (Table E1) were as defined by AECOM (2010) because that model provided more stable results for those scenarios.

Mitigation Alternatives

For the evaluation of mitigation alternatives in the Little Calumet River, a reduction factor was applied on the flow hydrograph based on the document Feature Design Memorandum No.1 Nonstructural Floodproofing measures (USACE, 1990).

The peak discharge diverted by the structure for the 100-years (24-hours) was used as reference (2300 cfs). The difference between the peak flow without diversion (3930 cfs) and peak flow diverted to Lake Michigan (2300 cfs) equals the peak flow discharged by Little Calumet into CAWS with diversion (1630 cfs). A factor of 0.4 ($=1630/3930$) was applied to the entire Little Calumet 100-years hydrograph to account for the effect of diversion. Only Finite-TARP (pre-filled) conditions were considered.

Findings

The effect of the barriers and the new operational paradigm (lakefront gates permanently fully open) do have important consequences on the water levels in CAWS and therefore on flooding within some areas of the City of Chicago. This is particularly true for the north part of the system (North Shore Channel,

Table E1: Summary of hydraulic modeling scenarios

Scenario Code Name	Barrier	Lake Michigan Level (CCD)	TARP	Storm event (Return Period)	Mitigation Work at Little Calumet
S19	YES	0	Finite	100-years	No
S115	No	0	Finite	100-years	No
S17	Yes	0	Infinite	100-years	No
S117	No	0	Infinite	100-years	No
S20 / S16	Yes	3	Finite	100-years	No
AE002	No	3	Finite	100-years	No
S18	Yes	3	Infinite	100-years	No
AE004	No	3	Infinite	100-years	No
S501/S503	Yes	3	Finite	500-years	No
AE503	No	3	Finite	500-yers	No
S502/S504	Yes	3	Infinite	500-years	No
AE504	No	3	Infinite	500-years	No
AEM101	Yes	3	Finite	100-years	Yes

North Branch, Mainstem, and South Branch) because the ability to control water levels in the system using Lockport would be lost on the lakeward side of CAWS with the South Branch Barrier.

Lake Michigan becomes a dominant factor for water levels in CAWS with the barriers and the fully open controlling works by the lakefront, particularly near the Wilmette Pumping Station and within the Mainstem Chicago River. If an extreme storm hits the City when Lake Michigan water levels are high there would be a greater risk of basement flooding than for the current condition (no barriers), even for reduced flood-peak levels in CAWS. The reason is that flooding in Chicago is not necessarily caused by overbank levels in CAWS, but by sewer backups. This happens when high levels in CAWS prevent the tide gates on the CSO outfall from opening, resulting in water backing-up in the sewer system. From the simulations results, the only area where overbank flows may occur during extreme rainfall events is by the confluence of North Branch, North Shore Channel, and Chicago River.

On the other hand, with low levels of Lake Michigan (0 CCD) the peak water levels in CAWS near the lakefront (Columbus Dr.) are significantly lower with the barriers in place and the fully open controlling works than under current conditions (no barriers). Therefore, as explained above, there would be a lower chance of flooding Chicago by sewer backup. Only during "dry" conditions are water levels in CAWS lower than for current conditions, but this is not relevant for flooding of the City of Chicago.

A side effect of the barriers is that flow volumes to Lake Michigan would be increased because any CSOs from outfalls and pumping stations, effluents from O'Brien WRP, and inflows from the North Branch would be evacuated through the lakefront gates.

On the Lockport side of the barriers flow discharges are reduced in presence of the barriers. In that case the

upper reach of the Chicago Sanitary and Ship Canal (CSSC) would basically convey only CSOs from the Racine Avenue Pumping Station (RAPS) down to the Stickney WRP. On the Cal-Sag and Calumet River branch, Little Calumet River is the most important inflow into CAWS. Because of the reduction of the discharge in CSSC by the barrier, peak levels are lower at the Cal-Sag Junction and the Cal-Sag Channel has enough conveyance (transport capacity) for draining the water towards Lockport with no significant variations on maximum water levels by O'Brien Lock & Dam, except for 500-year storm with Finite-TARP, and lake level at +3 CCD. Therefore, in general terms, flood risk in the south portion of the system is reduced in presence of the barriers.

The following are other findings on this study:

- When the barriers are in place and the gates are permanently open, Lake Michigan becomes the dominant factor on the water levels in CAWS in the downtown area and North Shore Channel. With high water levels in the Lake the barriers would keep CAWS higher during dry weather and pre-storm conditions than without the barriers. But, when Lake Michigan levels stays near historic minimum, water levels on the lakeside of CAWS would be lower than for current “ideal” conditions, and navigation would be impacted. This is because the regulation capacity of Lockport and the controlling works at the Lakefront would be lost with the barriers.
- Storage capacity of CAWS that allows for flow reversal minimization to Lake Michigan would be significantly reduced with barriers and new operation because the lakefront gates would remain open, thus subject to levels at Lake Michigan.
- On the Mainstem Chicago River (by Columbus Dr.) the peak flow would be reached earlier than for current conditions, because the water would flow straight to Lake Michigan instead of being partially stored in the canals. In case of flooding this means shorter response time for the City to respond to a flooding event.
- Water levels by the confluence of North Branch and North Shore Channel (by Lawrence Ave.) are strongly influenced by flows coming from the North Branch. At the same time, high levels in Lawrence Ave may have backwater effects on North Branch, thus reducing its draining capacity and increasing the risk of flooding due to backups through submerged pipes and/or by overbank flow on that area.
- Most of the CSOs are located on the lakeside of the north barrier (Chicago River South Branch, North Branch, and Mainstem). Without the barriers these CSOs regularly flow southward through Lockport or would be stored in CAWS until the lakefront gates are open, if necessary, for avoiding overbank levels. In this manner reversal flows to Lake Michigan are currently minimized without barriers. However, with the barriers in place, most of the CSOs would be sent straight to Lake Michigan, mostly through the Mainstem Chicago River.

- On the south part of the system the barriers reduce the flow through the CSSC as most CSO would flow to Lake Michigan. By 31st & Western (Lockport side of barrier) the flow is basically limited to CSO discharges from RAPS (max. flow is about 5,000 cfs). Other significant inflow is Stickney WRP (2,500 cfs). On the Calumet River, Little Calumet River is the most important inflow into CAWS. By the south barrier, on the Lockport side, water levels are not strongly affected by the barriers, except for the condition 500-years, Finite-TARP (pre-filled tunnels condition), and high water levels at Lake Michigan (+3 CCD). In that case water level without the barrier is much higher, because of high flows from Little Calumet, and a reduced capacity of Cal-Sag Channel due to backwater effects by CSSC. Thus, for such extreme condition the barriers would alleviate in some manner the risk of flooding.
- Close to the lakefront (Columbus Dr., Wilmette Pumping Station) the probability of exceeding critical levels (as defined by MWRDGC in its operation manual) is lower than for stations at inner locations (Lawrence Ave, Grand Ave, and Roosevelt Rd.), where probabilities are increased in the presence of the barrier. Most significant increments are for the case 100-year storm, Finite-TARP, and lake level at +3 CCD at Lawrence Ave. (+15 %), Roosevelt Rd. (+36%) and Grand Ave (+7%). These critical levels do not indicate overbank flow in CAWS, but were considered as a reference in this study as they define when flow reversals to Lake Michigan begin under current operation by MWRDGC.
- The effect of the mitigation works at Little Calumet River has little impact on flood-peak levels and discharges in Cal-Sag Channel and CSSC for the 100-years storm event. Even without the mitigation work the flood control structures at Lockport have enough convey capacity to keep water levels below critical (as defined by MWRDGC) during the entire period at O'Brien Lock & Dam, and most of the time at Sag-Junction (>95%).
- The mitigation works play a more important role on the 500-year storm event. The admissible (or critical) level at O'Brien Lock & Dam is exceeded by 3 ft, about 20% of the time primary due to flow coming from Little Calumet River. By reducing the flow hydrograph for about 60%, the maximum admissible level (3.5 ft) will still be exceeded, but for a shorter period (10%).

Recommendations

- Estimates on CSO volumes and hydrographs discharge into CAWS would gain accuracy with a model that accounts for river stage and open/close tide gates at outfalls.
- Better estimates of discharge coefficients at controlling works gates could be obtained with more sophisticated numerical or physical models that account for complex 3D flows near the gates and proximities.
- In order to avoid large variations on water levels during dry weather, operation rules of turbines and sluice gates at Lockport could be set to a goal or target level plus a small tolerance in monitoring

locations. In this manner opening/closing gates would not be governed by maximum and minimum admissible water levels in the system all the time.

- The discharge capacity of controlling works at Lockport is affected to some extent by the conditions of Des Plaines River. A better understanding of the hydraulics on that matter would improve the estimate of discharge capacity at Lockport Controlling Works, a major flood-control feature in the CAWS.

Contents

Executive Summary	i
List of Figures	xi
List of Tables	xiii
1 Purpose and Scope	1
2 Chicago Area Waterways System	2
2.1 Controlling Works	3
2.1.1 Lockport Powerhouse and Controlling Works	3
2.1.2 OBrien Lock and Dam	3
2.1.3 Chicago River Controlling Works	3
2.1.4 Wilmette Pumping Station	4
2.2 Mid-System Barriers	4
2.3 Chicago Waterways Storage Capacity	5
2.4 Figures and Tables	6
3 Methods and Tools	11
3.1 HEC-RAS model	11
3.1.1 Geometric schematization	11
3.1.2 Flow data	12
3.2 Modeling Scenarios	13
3.2.1 Storm events	13
3.2.2 Mid-System Barriers	14
3.2.3 Water levels in Lake Michigan	15
3.2.4 Mitigation alternatives	15
3.3 Location of virtual gages in CAWS	15
3.4 Combined Sewer Overflows (CSO)	16
3.5 Lockport operation rules	16
3.6 Figures and Tables	18
4 Results	28
4.1 100-year storm event	28
4.1.1 Lake Michigan at 0 CCD and Finite-TARP capacity	28
4.1.2 Lake 0 CCD and Infinite-TARP capacity	29

4.1.3	Lake +3 CCD and Finite-TARP capacity	29
4.1.4	Lake +3 CCD and Infinite-TARP capacity	30
4.2	500-year storm event	31
4.2.1	Lake +3 CCD and Finite-TARP capacity	31
4.2.2	Lake +3 CCD and Infinite-TARP capacity	32
4.2.3	Mitigation works	33
4.3	Fraction of time critical levels are exceeded	33
4.4	Figures and Tables	35
5	Findings	53

List of Figures

2.1	General view of Chicago Area Waterway System today (Credit: MWRDGC)	6
2.2	Schematic of Chicago Area Waterways System (HEC-RAS Model domain)	7
2.3	Location of barriers for Mid-system alternatives	8
2.4	Total storage volume rating curves	9
2.5	Storage volume rating curves for CAWS reaches	9
3.1	Submerged discharge coefficient for CRCW South Gates	20
3.2	Submerged discharge coefficient for CRCW North Gates	20
3.3	Discharge coefficient for CRCW Sector gates (Lock)	21
3.4	Intensity and cumulative precipitation 100-years storm	21
3.5	Intensity and cumulative precipitation synthetic 500-years storm	22
3.6	500-years storms of different durations and corresponding volumes of CSOs	22
3.7	Location of monitoring virtual gage stations	23
3.8	Lake wide monthly averaged water level - Lake Michigan from 1950 - 2013	24
3.9	Diversion hydrograph with mitigation structure in Little Calumet for 100-years (Source: USACE, 1990)	25
3.10	CSO hydrograph for 100-years storm with Finite- and Infinite- TARP capacity	26
3.11	Volumes of water drained into CAWS during 100-years storm event for finite-and infinite-TARP capacities	26
3.12	CSO hydrograph for 500-years storm with Finite- and Infinite- TARP capacity	27
3.13	Cumulative CSO hydrograph for Finite- and Infinite-TARP capacities for 500-year storm events	27
4.1	Effect of barrier on water level and flow discharge at Wilmette PS	36
4.2	Effect of barrier on water level and flow discharge at Columbus Dr	36
4.3	Effect of barrier on water level and flow discharge at Lawrence Ave	37
4.4	Effect of barrier on water level and flow discharge at O'Brien Lock & Dam	37
4.5	Effect of barrier on water level and flow discharge at Columbus Dr.	38
4.6	Effect of barrier on water level and flow discharge at Wilmette Pumping Station	38
4.7	Effect of barrier on water level and flow discharge at O'Brien Lock & Dam	39
4.8	Effect of barrier on water level and flow discharge at Wilmette Pumping Station	39
4.9	Effect of barrier on water level and flow discharge at Columbus Dr.	40
4.10	Effect of barrier on water level and flow discharge at Lawrence Ave.	40
4.11	Effect of barrier on water level and flow discharge at 31st & Western (Lockport side of south branch barrier)	41
4.12	Effect of barrier on water level and flow discharge at O'Brien Lock & Dam	42
4.13	Effect of barrier on water level and flow discharge at Columbus Dr.	42

4.14	Effect of barrier on water level and flow discharge at Lawrence Ave.	43
4.15	Effect of barrier on water level and flow discharge at 31st & Western.	43
4.16	Effect of barrier on water level and flow discharge at O'Brien Lock & Dam.	44
4.17	Effect of barrier at Columbus Dr. / 500-year storm.	44
4.18	Effect of barrier at Lawrence Ave. / 500-year storm.	45
4.19	Effect of barrier at Wilmette PS / 500-year storm.	45
4.20	Effect of barrier at 31st & Western / 500-year storm.	46
4.21	Effect of barrier at OBrien Lock & Dam / 500-year storm	46
4.22	Effect of barrier at Columbus Dr. / 500-year storm	47
4.23	Effect of barrier at Lawrence Ave. / 500-year storm	47
4.24	Effect of barrier at Wimette PS / 500-year storm	48
4.25	Effect of barrier at 31st & Western / 500-year storm	48
4.26	Effect of barrier at OBrien Lock & Dam / 500-year storm	49
4.27	Effects of mitigation works at OBrien Lock & Dam / 100-years storm	49
4.28	Effects of mitigation works at Sag-Junction /100-years storm	50
4.29	Effect of mitigation works at OBrien Lock & Dam / 500-years	50
4.30	Effect of mitigation works at Cal-Sag Junction / 500-years	51
4.31	Fraction of time critical levels are exceeded at Wilmette PS	51
4.32	Fraction of time critical levels are exceeded at Roosevelt Rd.	52
4.33	Fraction of time critical levels are exceeded at Lawrence Ave.	52

List of Tables

3.1	Summary of hydraulic modeling scenarios	18
3.2	Virtual gages for computed water levels and flow discharges	18
3.3	Operation of controlling works at lakefront for scenarios without barriers	19
4.1	Fraction of time that critical water levels are exceeded on the lakeside of South Branch Barrier, 100 year storm	35
4.2	Fraction of time that critical water levels are exceeded on the Lockport side of South Branch Barrier, 100 year storm	35

1 Purpose and Scope

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2 Chicago Area Waterways System

The City of Chicago, Illinois (IL) and many of its suburbs lie within the glacial Lake Chicago Plain. The Lake Chicago Plain encompasses the Chicago, Des Plaines, and Calumet Rivers. Early explorers discovered and used the Chicago Portage, an area within Mud Lake that was only 4.6 meters (m) above the level of Lake Michigan and near the watershed divide between the Mississippi River and the Great Lakes basins. Because of the low relief, the area was poorly drained. The level of Lake Michigan in the late 1800s was only 0.61 m below the riverbanks, making subsurface drainage ineffective. Flow from the North Branch Chicago River (NB) and the South Branch Chicago River (SB) joined just north of present-day Lake Street and flowed eastward into Lake Michigan. Sewage discharged into the Chicago River (CR) caused serious health hazards during the late 1800s as the river flowed into the lake and the sewage affected the drinking water supply from Lake Michigan. In 1900, a canal dug by the Sanitary District of Chicago (District) linking the CR to the Des Plaines River (Mississippi River basin) was completed and reversed the flow in the CR. This canal, the Chicago Sanitary and Ship Canal (CSSC) is 45 kilometers (km) from the SB to Lockport, IL. The CSSC carries urban drainage and wastewater away from the city and Lake Michigan. Other improvements in drainage were also implemented. In 1910, the North Shore Channel (NSC), constructed by the District connected Lake Michigan at Wilmette to the NB allowing the capture of sewage from North Shore suburbs and providing lake water to be used to flush sewage in the NB. In 1922, the Calumet Sag Channel (CSC), also constructed by the District, connected the Little Calumet River (LCR) to the CSSC. This provided for the partial reversal of the LCR and allowed sewage draining into this river and the Calumet River to be diverted away from Lake Michigan. The CSC has since been widened and improved for commercial navigation and complete reversal of the LCR. Collectively, all these improved and controlled waterways are referred to as the Chicago Waterway System (CAWS).

Today (2013), the CR flows west from Lake Michigan, through downtown Chicago, and joins flow coming from the NB where it enters the SB/CSSC. Outflow from the entire CAWS is controlled by the Lockport Powerhouse and Controlling Works (near Joliet, IL). Three lakefront structures control inflow from Lake Michigan and the infrequent release of excess flood waters to the lake during extreme hydrologic events (i.e. intense rainfall). The CR is controlled by the Chicago River Controlling Works (CRCW) and the Chicago River Lock. The NSC is controlled by the Wilmette Pumping Station and Sluice Gate. The LCR is controlled by the OBrien Lock and Dam on the Calumet River south of 130th Street in Chicago (Figure 2.1 and 2.2).

During the summer months, water from Lake Michigan flows into the CR through sluice gates in the CRCW and through the Chicago River Lock at CRCW. Flow of water from Lake Michigan through the CRCW sluice gates into the CR during the summer months, called discretionary diversion; is used to preserve or improve the water quality in the CR, SB and CSSC. During winter, flow from Lake Michigan into the CR is small and typically results from leakage through the gates and sea walls at CRCW and from occasional

navigational lockage. Other contributions to the CR discharge include water from direct precipitation and discharges of water used for cooling purposes from neighboring buildings. The NB carries runoff from a 100 square mile watershed and treated municipal sewage effluent released by the TJ O'Brien Water Reclamation Plant (before called North Side WRP) located 16 km upstream from the confluence of the branches. All of this effluent is transported down the SB into the CSSC and then to the Des Plaines and Illinois Rivers.

2.1 Controlling Works

2.1.1 Lockport Powerhouse and Controlling Works

The Lockport Controlling Works (LPCW) on the Chicago Sanitary and Ship Canal (CSSC) are located at Romeoville, IL. When the turbines and sluice gates at Lockport Powerhouse are insufficient, these structures are operated for diverting the flow from CAWS to Des Plaines River. The LPCW includes seven 30 ft by 16 ft high sluice gates with invert at -15 ft (CCD) according to MWRDGC and AECOM (2010).

The Lockport Powerhouse (LPPH) is the downstream end of the CSSC and the CAWS. Water is diverted from the CAWS through two turbines and nine sluice gates (14 height by 9 width; invert at -28.48 ft) onto Des Plaines River. The facility also includes two locks for navigational purposes. However the locks were not included in the model because they are closed during wet weather for flood management. The tail-water elevation at LPPH is controlled by the Brandon Dam on the Illinois River, and it was set at -41 ft.

On the Des Plaines River side of the controlling works, it was assumed a high water level condition in Des Plaines River when the gates are open. This assumption was for including the effect of Des Plaines on the discharge capacity of the controlling works.

2.1.2 OBrien Lock and Dam

The OBrien Lock and Dam is the southernmost connection of the CAWS with Lake Michigan. The lock chamber was reduced to a single sluice gate 110 ft wide at an invert -26.50 ft. The top of both gate and dam is at +5.5 ft. In addition, the dam has 4 sluice gates at invert -13 ft with dimensions of 10 wide × 10 of height. This simplification should not have a significant effect on the overall results AECOM (2010).

2.1.3 Chicago River Controlling Works

The Chicago River Controlling Works (CRCW) is located at the lakefront end on the Mainstem Chicago River. This was the natural outlet of the Chicago River before it was reversed when the CSSC was open for

draining into the Des Plaines River. It includes several structures represented in HEC-RAS by inline and lateral weirs and gates.

The first set of structures is the U.S. North Pier and North Basin Wall, which includes the North Gates: Four sluice gates (10×10) with invert of -18 ft, and weir top above +6.8 ft. The lock chamber is bounded by the North and South walls defined as weirs with top +7ft, except on the middle of the North wall where the lock control house is located (top at +419.8 ft). The Turning Basin Cutoff Wall (south) is the fourth set of structure. It includes 4 sluice gates (10×10) with invert of -17.69 ft that are operated for flood control. The last set is the Lock gates, which were defined as Inline Structures in HEC-RAS. Two of them define the East- and Westbound of the Lock chamber. Both of them include 10 gates with invert of -24.44 ft, 40 ft height, and 8 ft width.

2.1.4 Wilmette Pumping Station

Wilmette controlling works currently operates only for flood control and navigation diversions, though it was originally designed as a navigational lock. It is located at Wilmette, IL on the northern boundary of the CAWS on the Lakefront. In the model the structure is represented by a 120 ft long weir at an elevation of +6 ft. A 32.0 ft wide by 15.5 ft high sluice gate is located on the south side. A lateral structure was defined for accounting overflows onto Sheridan Avenue when water reaches an elevation of +6 CCD.

The single gate at Wilmette was replaced recently by three smaller gates. Unfortunately an updated geometry was not available to be included in the present model.

2.2 Mid-System Barriers

For the scenarios with barriers the computational domain was split upstream of the confluence with Bubbly Creek to account for the south Branch Barrier (Figure 2.3). A no-flow boundary condition was set up at this location, while the water level was to be computed with the HEC-RAS model. Also it was assumed that the lakefront controlling works remain fully open all time. Under this operative scheme the top priority is flood control for the City of Chicago regardless of quality issues, reversal flows, or limitations on diversion accounting.

The South barrier is to be placed between OBrien Lock & Dam (Figure 2.3). A no-flow condition was set up to represent the separation effect by the barrier. The operation of Lockport powerhouse (LPPH) turbines and flood control gates, and Lockport Controlling Works (LPCW) follows the Metropolitan Water Reclamation District of Greater Chicago (2013) for both conditions with and without barriers.

2.3 Chicago Waterways Storage Capacity

An important impact of the barriers on the CAWS hydraulics is the reduction of the storage capacity in the waterways. In the case of the lakeside of the South Branch Barrier this is aggravated if the lakefront gates remain open, even during dry weather. A volume rating curve is presented in Figure 2.4. Corresponding volumes for water levels ranging from -35 CCD to 10 CCD were computed from the USGS & UIUC bathymetric survey data (2008) using the Surface Volume (3D Analyst[®]) tool in ArcGIS 10.1[®] assuming a constant level in the entire domain. In this manner it was possible to develop volume rating curves for each reach of the CAWS as shown in Figure 2.5.

If we consider that the flood control levels on the lakeside of the barrier to play with when a storm hits the city are -2 CCD and 4 CCD, the flood control volume in CAWS is reduced from 4 BG (=13.6 9.6) to 0.8 BG (=2.8 2.0), i.e. a reduction of 80%.

2.4 Figures and Tables

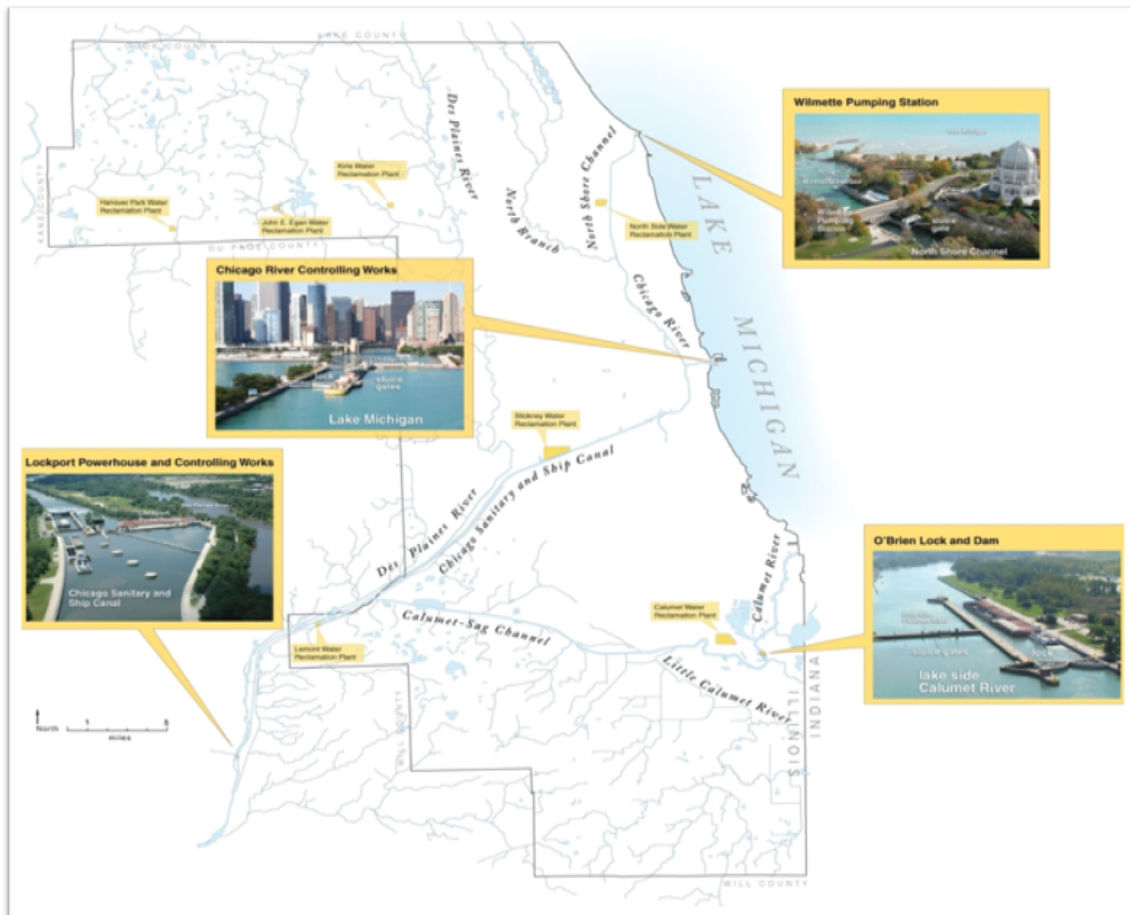


Figure 2.1: General view of Chicago Area Waterway System today (Credit: MWRDGC)

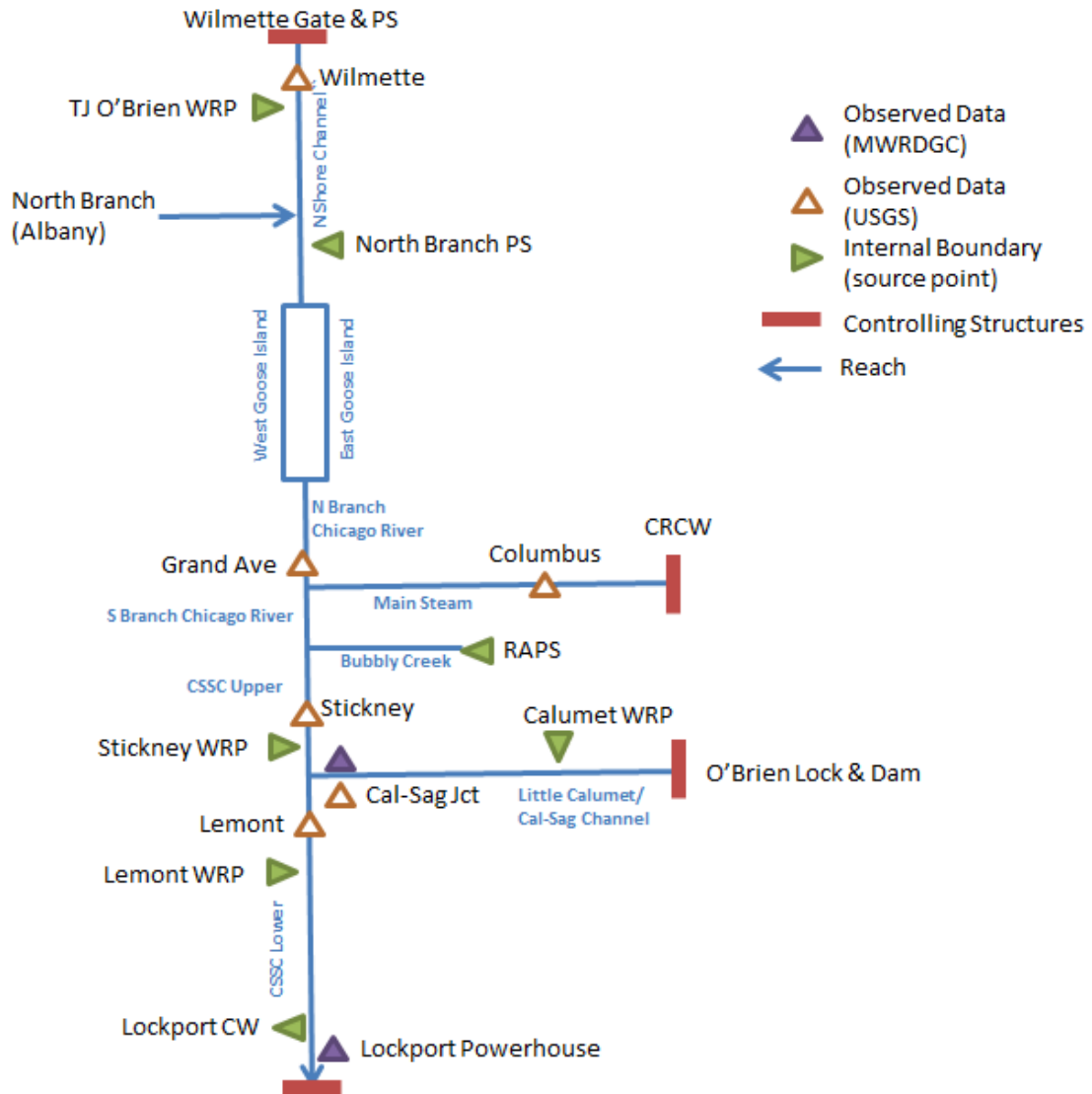


Figure 2.2: Schematic of Chicago Area Waterways System (HEC-RAS Model domain)

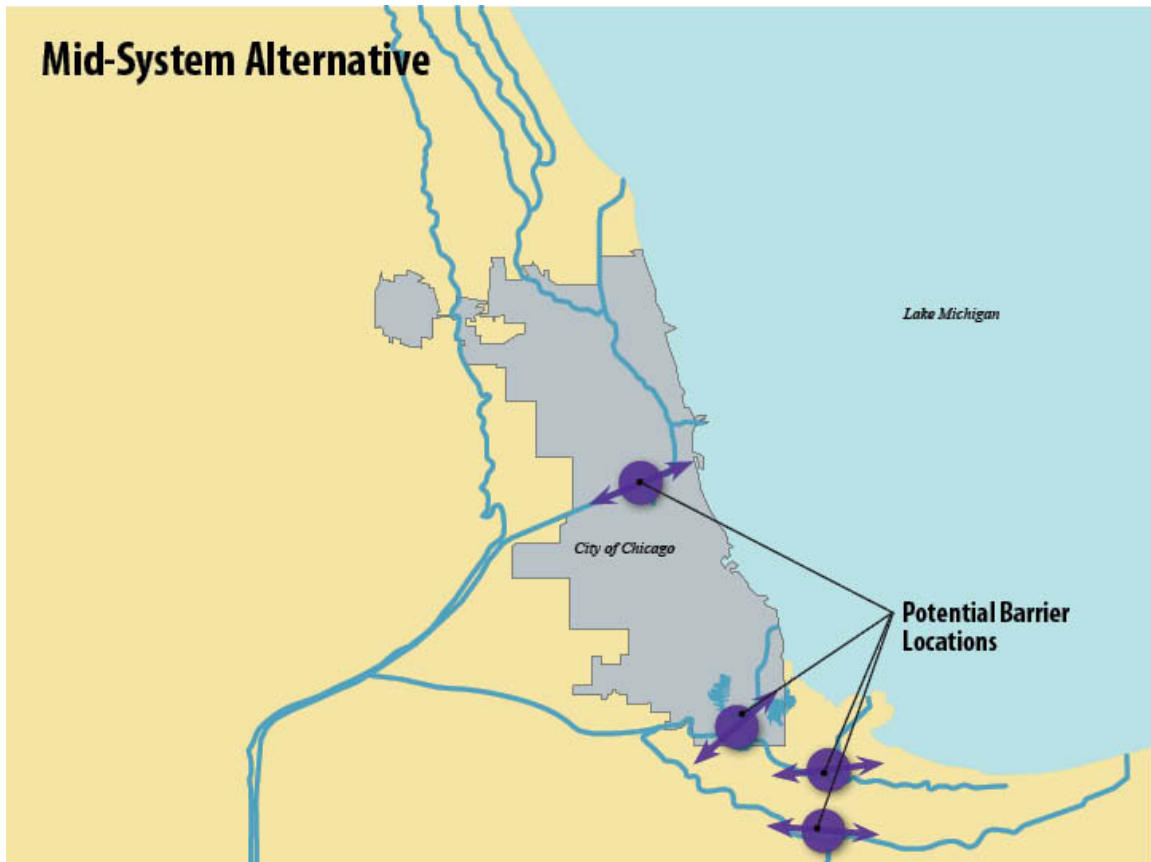


Figure 2.3: Location of barriers for Mid-system alternatives
(Only Barriers 1 and 2 are considered in this study)

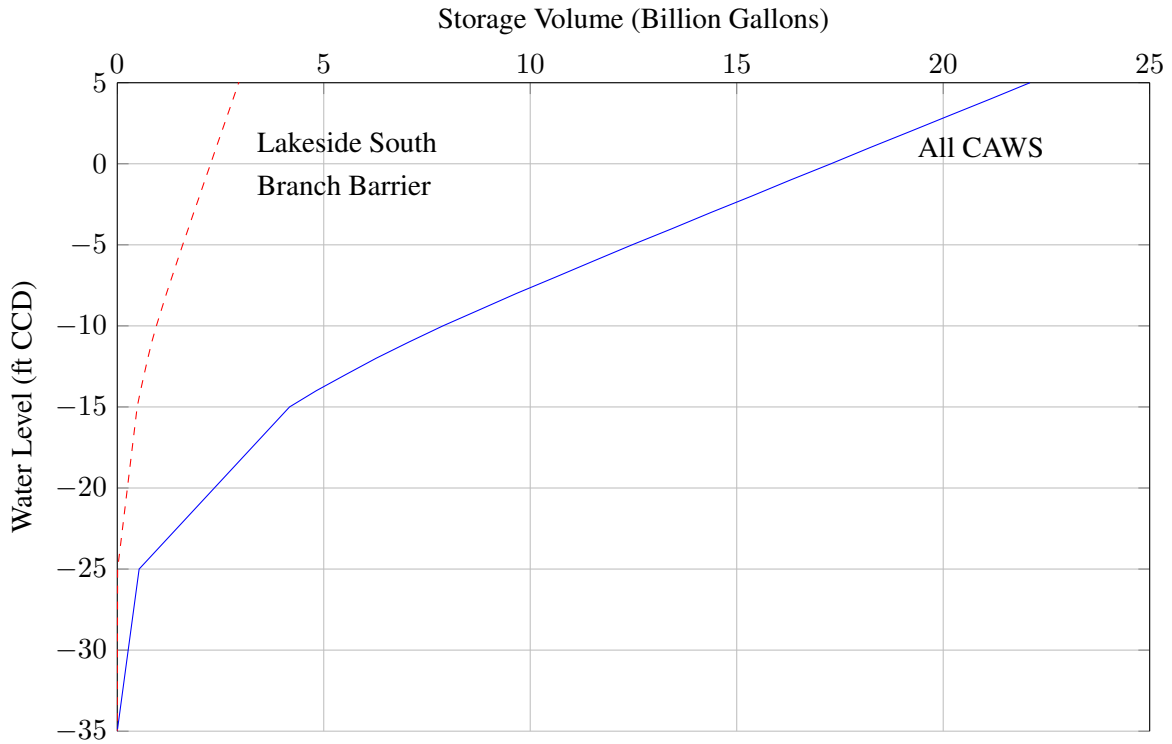


Figure 2.4: Total storage volume rating curves

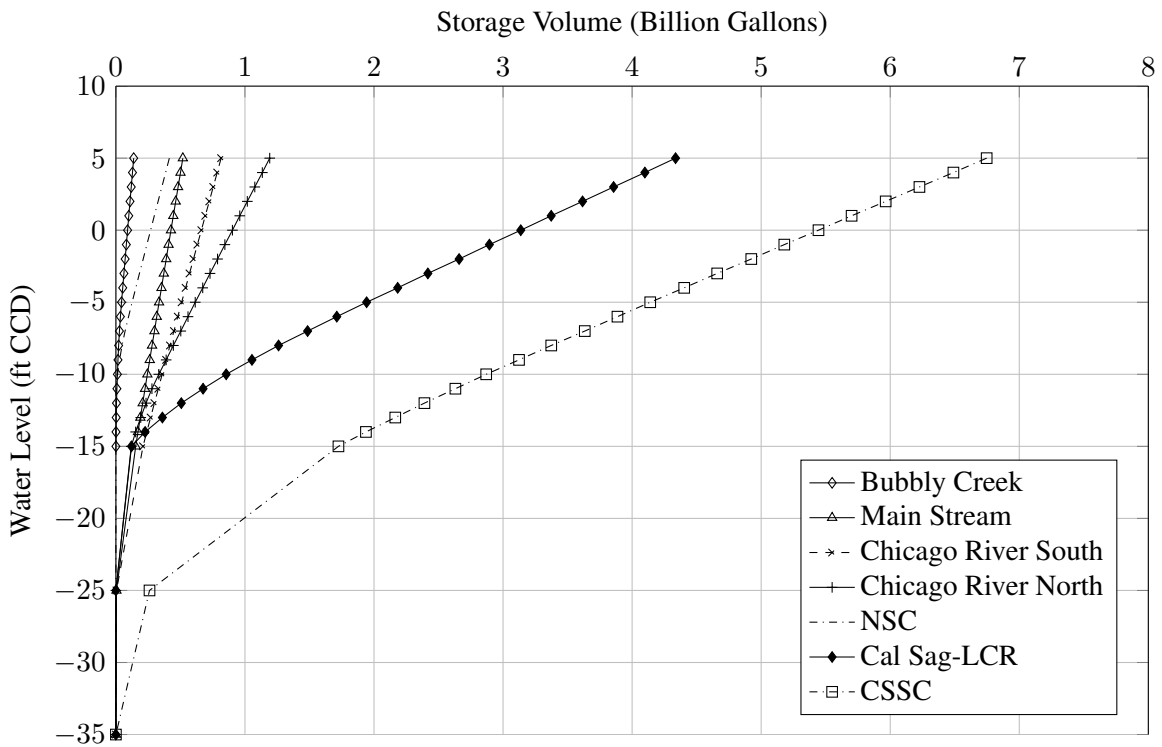


Figure 2.5: Storage volume rating curves for CAWS reaches

3 Methods and Tools

3.1 HEC-RAS model

The Hydrologic Engineering Centers River Analysis system (HEC-RAS) is a widely used one-dimensional hydraulic model. In this study the unsteady flow model was implemented. It allows simulating the hydraulic behavior of CAWS under time changing conditions and operation of structures.

The unsteady module of HEC-RAS is based on the principles of conservation of mass (continuity equation) and momentum. A brief discussion on the derivation of those equations is presented in the Hydraulic Reference Manual of HEC-RAS, based on a more detailed article by Liggett and Cunge (1970).

Basic data required by the unsteady HEC-RAS model includes Geometry Schematic (stream alignments, cross-sections, junction nodes, etc.), flow data (boundary and initial conditions: flow or stage hydrographs, lateral inflows, rating curves, operation of structures, etc.), and computational parameters (time step, simulation period, computational tolerances, etc.). Following are the main characteristics of the HEC-RAS model that was implemented for CAWS.

3.1.1 Geometric schematization

Stream alignments and cross-sections were initially based on a bathymetry surveyed by USGS and UIUC in 2008. However, due to model instabilities the schematization by AECOM (2010) was considered as a base, with modifications on boundaries, structures, and operational rules when necessary for the purpose of this study. A fixed Mannings roughness of 0.03 was set for the entire domain. Further calibration of this parameter was not performed because it was observed a low sensibility of water levels to this parameter. This is not surprising given the low velocities of the flow in the system.

HEC-RAS allows defining inline and lateral structures in the geometry schematization. Only sluice gates and Overflow (Open Air) gates were used in CAWS model. Inline sluice gates (flow through structures continues in same stream) were defined at Wilmette, OBrien Lock & Dam, and Lockport Powerhouse. North and South gates at CRCW, Lockport Controlling Works and turbines were defined as sluice gates in lateral structures (diverting flow into another reach). This type of gates follows the following relation:

$$Q = CWB\sqrt{2gH} \quad (3.1)$$

Where: Q = flow discharge [L³T⁻¹]
 C = coefficient of discharge [-]
 W = length of gate (along cross section) [L]
 B = gate opening [L]
 g = acceleration of gravity [LT⁻²]
 H = Upstream energy head [L]
(Difference Tail and Head water levels)

However, if downstream submergence occurs HEC-RAS solves the equation:

$$Q = CWB\sqrt{2g3H} \quad (3.2)$$

O'Brien Lock and CRCW sector gates were modeled as open air overflow gates following the equation

$$Q = CLH^{3/2} \quad (3.3)$$

Geometric characteristics of each structure are described in Section 2.1.

Sluice gates coefficients (C) for CRCW North and South Gates were chosen to follow rating curves for fully open conditions developed by UIUC using a 3D numerical model Kim et al. (2014). In order to find the most appropriate values of C the Chicago River Mainstem alone was modeled under steady flow conditions using HEC-RAS unsteady flow module. Best C -values correspond to closest head losses estimated with the model given Lake level -3 CCD and fully open gates (as assumed by Kim et al. (2014)). For a given flow discharge entering Mainstem at Wolf Point and leaving through fully open gates, there is a corresponding water level at CAWS. Since lake level was a boundary condition the head losses at the structures can be computed directly. From Figures 3.1 and 3.2 best matches were for $C = 0.7$ at South Gates (Figure 3.1) and $C = 0.6$ at North Gates (Figure 3.2), and C is the coefficient for submerged orifice.

A similar exercise was done for sector gates (Lock), but none of the values for C provided satisfactory results (Figure 3.3). Therefore the default value in HEC-RAS ($C=2.6$) was adopted. For Lockport pit gates and turbines values suggested by Kiefer (nd) were defined as $C=0.613$ and $C=0.35$, respectively. At Wilmette $C = 0.5$ for sluice gate, and at O'Brien Lock & Dam $C = 0.5$ for sluice gates and $C = 3$ for lock gate. The latter values as defined by AECOM (2010).

3.1.2 Flow data

Boundaries at lake front and downstream of Lockport were defined by stage hydrographs using historic data (historic 2008 scenario) or a fixed level as defined for different scenarios. Flow hydrographs from USGS

stations at North Branch Chicago River at Albany, and Little Calumet River were used as upstream boundary conditions for those reaches. CSOs estimated with the CityModel were included in the model as lateral local inflows.

Operation of lateral and Inline structures at Wilmette PS, CWCR, O'Brien Lock & Dam and Lockport Powerhouse and controlling Works were defined with a set of operation rules based on reference levels in CAWS. More details on the criteria is presented in Section 2.1.

3.2 Modeling Scenarios

A total of 16 scenarios are analyzed in this report. Each one represents a different combination of the following variables affecting the CAWS (Table 3.1):

- Precipitation event: 100-year (historic event of September 13th - 15th 2008) and 500-year storm events.
- Presence of barriers: Current conditions (no barriers) vs. proposed mid-system (two barriers)
- TARP capacity: independent of total storage volume of TARP, it may happen that a previous storm reduces the available storage of TARP for runoff retention due to an extreme event (as in September 2008). This condition is represented by a Finite-TARP in the CityModel (García and Schmidt, 2013)). On the other hand, if TARP capacity is so large that is not a concern in terms of storage capacity; an Infinite-TARP condition is set in the CityModel for the estimation of CSOs into CAWS.
- Water levels in Lake Michigan: Two elevations were proposed by GLC for evaluating the effect of Lake Michigan on CAWS during extreme storm events: 0 CCD and +3 CCD. These values represent normal and high water levels in Lake Michigan.
- Mitigation works in Little Calumet River: With a barrier between Lake Calumet and O'Brien Lock and Dam, there is a concern if the Cal-Sag canal has enough capacity for conveying all the flow into the CSSC. With the south barriers any flow from Little and Grand Calumet rivers, and the Calumet WRP has to be drained into the Chicago Sanitary and Ship Canal (CSSC). The effect of a mitigation alternative for diverting a fraction of the Little Calumet into Lake Michigan and reduce its discharge into CAWS is evaluated.

3.2.1 Storm events

A storm event can be characterized by its intensity (volume of rain falling per unit time per unit area, usually inches per hour) and duration. Different combinations of these two variables are related to certain probability of occurrence of similar or larger events during a single year. The return period is simply the inverse of such

probability, and it is commonly used for referring a storm on a hydrologic analysis. For instance, a 5-year storm event (return period is 5 years) has a probability of occurrence during a single year of $1/5 = 0.2$ (or 20%). For the purposes of the present analysis two storm events were defined: 100- and 500-years.

100-years storm Instead of using a synthetic storm for the 100-year storm, a historic event was considered. The storm event of September 13-15th 2008 was chosen as it has become a common reference for flood analysis in the City of Chicago (Figure 3.4). The total precipitation within this period was about 6.5 inches, distributed in two consecutive storms: the first one with maximum intensity of 0.7 in/hr on average, and the second one with a maximum intensity of 0.3 in/hr. Because of its bi-modal distribution on time (double peak) it allows to consider a critical situation when a storm hits the city right after another one. This is a strenuous situation for a flood control system, since the first event may reduce substantially the system capacity to respond during the second storm. In the context of the City of Chicago this means that even with a large enough capacity of TARP for containing a storm event, it may occur (and has occurred in the past) that there is not enough available storage for a second storm.

500-years storm The 500-yrs storm (prob. Occurrence of 0.2% in a year) was defined as a synthetic event. The NOAA Atlas 14 Intensity-Duration-Frequency curves (IDF) were used as reference for defining the maximum intensity and duration of the storm (Figure 3.5). The selection of the 500-year/24-hours storm was done after comparison of CSO estimates using the CityModel for different storm events. Figure 3.6 summarizes the results for CSOs in Calumet, Mainstem Des Plaines system (MSDP) and total (Calumet + MSDP), and the 24 Hours events provides a reasonable value. The maximum intensity for 500-years 24H event is close to 0.8 in/hr and the total volume CSO for Finite-TARP is about 20 BG (RAPS and NBPS included).

For the 500-years storm the CSOs put into CAWS about 0.9 BG and a flow discharge peak close to 4,500 cfs (total) for Infinite-TARP, while for Finite-TARP the estimate total CSOs volume is 15.5 BG with a maximum flow peak of 42,000 cfs (total).

3.2.2 Mid-System Barriers

For the scenarios with barriers the computational domain was split upstream of confluence of Bubbly Creek (Figure 12). A no-flow boundary condition was set up at this location, while the water level was to be computed with the HEC-RAS model. Also lakefront controlling works remain fully open all time. Under this operative scheme the top priority is flood control for the City of Chicago regardless of quality issues, reversal flows, or limitations on diversion accounting.

The South barrier is to be placed between OBrien Lock & Dam (Figure 12). A no-flow condition was set up

to represent the separation effect by the barrier. The operation of Lockport powerhouse (LPPH) turbines and flood control gates, and Lockport Controlling Works (LPCW) follows the MWRDGC Dispatcher Manual for both conditions with and without barriers.

3.2.3 Water levels in Lake Michigan

Two conditions in Lake Michigan were considered in this analysis as boundary condition. Initially a level of +0 CCD (579.196 ft) was defined on the Lake by Wilmette, CRCW, and OBrien Lock & Dam. This represent is a normal condition of the Lake. The second value of +3 CCD (582.196 ft) was to represent a high Lake condition. Historic data compiled at NOAA on the Great Lake Hydro-Climate Dashboard (GLHCD) (Gronewold et al., 2013)) was used for verification (Figure 3.8).

3.2.4 Mitigation alternatives

The reduction factor for the hydrograph is based on the document Feature Design Memorandum No.1 Non-structural Floodproofing measures by USACE (1990) as provided by Paul Dierking from HDR.

The peak discharge diverted by the structure as in Plate A2-I-11 (100-year 24H event) was used as reference (2300 cfs). The difference between the peak flow without diversion (3930 cfs) and peak flow diverted to Lake Michigan (2,300 cfs in Figure 3.9) equals the peak flow discharged by Little Calumet into CAWS with diversion (=1630 cfs). A factor of 0.4 (=1630/3930) was applied to the entire Little Calumet 100-year hydrograph to account for the effect of diversion. Only Finite-TARP conditions were considered.

3.3 Location of virtual gages in CAWS

Key locations were defined in order to check peak and duration of high levels in the system for each one of the modeled scenarios. A total of 10 locations were considered for comparison of water levels and discharges for each modeled scenario (Figure 3.7 and Table 3.2)

Critical levels were defined at most of these locations as the maximum admissible level at lakefront structures (Wilmette, CRCW, and OBrien L&D) based on MWRDGC (2013). For the rest of locations critical levels were defined based on maximum historic levels for September 13-15th 2008, as they are strongly related to the operation of Lockport and lakefront gates. Critical levels for key locations along CAWS are shown in Table 3.2.

3.4 Combined Sewer Overflows (CSO)

Combined Sewer Overflows in the hydraulic model were as estimated with the City Model on InfoWorks García and Schmidt (2013). Two conditions of TARP were considered. The first one, Finite-TARP from herein, assumes a limited storage capacity of TARP. This condition represents a back-to-back storm event, in which a previous storm already filled up TARP tunnels and reservoirs, so that a considerable fraction of the precipitation drains into CAWS as CSO. This is considered a critical, but feasible scenario and it is independent of the actual capacity of TARP. Although it is true that an increased storage capacity of TARP would reduce the frequency of occurrence of such scenario, it is considered feasible and expected, as it has happened before in September 2008, and more recently in April 2013.

The second condition of TARP considered in this analysis, is that its capacity is much larger than the volume of water coming from a storm event (referred as Infinite-TARP from this point). In this case it is assumed that the interceptors, tunnels, and reservoirs have enough capacity to convey and/or store a humungous volume of water. In consequence, CSOs into CAWS are dramatically reduced. Some CSOs still may occur due to conveyance limitations in the system (bottle necks) rather than because of storage limitations. Each of these outfalls is included on the hydraulic model as a local lateral inflow.

For the 100-years storm an estimated total volume of 9.84 BG, and a maximum CSO discharge of 23,000 cfs (sum of all outfalls) with Finite-TARP condition were estimated for CAWS. While for Infinite-TARP 0.09 Billion Gallons (BG) and a peak discharge of 695 cfs were estimated (Figure 3.10 and 3.11).

The 500-year storm has an estimated total volume of CSO of 15.51 BG with a peak CSO discharge of 44,000 cfs (sum of all outfalls) with Finite-TARP. While for Infinite-TARP 0.88 Billion Gallons (BG) and a peak discharge of 3,470 cfs were estimated (Figure 3.10 and 3.13).

3.5 Lockport operation rules

The operation of controlling works on the lakefront boundaries of CAWS (Wilmette, CRCW, and OBrien Lock & Dam) and Lockport were based on the Dispatcher Manual (2013) by MWRDGC for flood control during wet weather. However, the operation paradigm was shifted so that once open, gates are not closed again (Table 3.3).

For the scenarios With Barrier the lakefront gates were fully open during the entire simulation period. On the scenarios Without Barriers, the criteria for gate opening are as stated in MWRDGC Dispatcher Manual (2013); however once they are open they are not closed again.

Lockport Powerhouse and Controlling Works are operated following the recommendations in MRDGC Manual. However, for some scenarios the operation of turbines was defined as a fixed discharge leaving

the system (2,500 cfs) for sake of model stability. The scenarios AE002, and AE004 (Table 3.1) were as defined in AECOM model (2010) for sake of stability.

On the Lockport boundary the operation was defined as follows:

1. Maximum/ Minimum (targets) admissible water levels at
 - (i) CRCW: -0.5 CCD/-3.0 CCD
 - (ii) O'Brien Lock & Dam: -0.5 CCD / -3.0 CCD
 - (iii) Cal-Sag Junction: -1.8 CCD / -4.0 CCD
 - (iv) Lockport CW: -2.0 CCD / -10 CCD
2. Maximize flow through turbines (maximum opening: 14 ft)
3. If turbines' gates are fully open and water levels are still above admissible, open Pit-Sluice gates (up to 9) in the following sequence (maximum opening: 14 ft):
 - (i) 7A & 7C
 - (ii) 4A & 4C
 - (iii) 3A & 3C
 - (iv) 7B
 - (v) 4B
 - (vi) 3B
4. If Pit-Sluice gates are fully open and water levels are still above admissible, open Lockport Controlling Works gates (up to 7) in the following sequence:
 - (i) CW1 & CW2
 - (ii) CW3 & CW4
 - (iii) CW5 & CW6 & CW7
5. If water levels drawdown below maximum admissible levels, close the gates in the inverse order

AECOM (2010) also defined a dry weather operation of gates based on target water levels at key locations, so that the water levels remain in a tighter interval around these values unless maximum or minimum water levels are reached. This option should be explored in future work with the HEC-RAS model by UIUC.

3.6 Figures and Tables

Table 3.1: Summary of hydraulic modeling scenarios

Scenario Code Name	Barrier	Lake Michigan level (CCD)	TARP	Storm event (Return Period)	Mitigation Work at Little Calumet
S19	YES	0	Finite	100-years	No
S115	No	0	Finite	100-years	No
S17	Yes	0	Infinite	100-years	No
S117	No	0	Infinite	100-years	No
S20/S16	Yes	3	Finite	100-years	No
AE002	No	3	Finite	100-years	No
S18	Yes	3	Infinite	100-years	No
AE004	No	3	Infinite	100-years	No
S501/S503	Yes	3	Finite	500-years	No
AE503	No	3	Finite	500-years	No
S502/S504	Yes	3	Infinite	500-years	No
AE504	No	3	Infinite	500-years	No
AEM101	Yes	3	Finite	100-years	Yes
SM501	Yes	3	Finite	500-years	Yes

Table 3.2: Virtual gages for computed water levels and flow discharges

Site	Reach	River Mile (aprox.)	Critical level (CCD)
Wilmette	North Shore Channel	340.79	5
TJ O'Brien WRP	North Shore Channel	336.5	-
Lawrence Ave	Chicago River North	326.86	4
Grand Ave	Chicago River North	326.05	3.5
Columbus	Chicago Main River	326.62	3.5
Roosevelt Rd	Chicago River South Branch	324.35	2
31 St & western Ave	Chicago Sanit. and Ship Canal	321.5	-1.5
Stickney	Chicago Sanit. and Ship Canal	315.23	-
O'Brien L&D	Calumet River	325.75	3.5
Lemont	Chicago Sanit. and Ship Canal	302.49	-

Table 3.3: Operation of controlling works at lakefront for scenarios without barriers

Location	Structure	Begins to open (ft-CCD)	Opening rate (ft/min)	Max. Open (ft)
Wilmette	Sluice Gates	5	1	18
	North Gates	3.2	1	10
CRCW	South Gates	3	1	10
	Sector gates (Lock)	3.4	4	40
OBrien L&D	Lock gates	3.3	5.5	27
	Sluice gates	3	1	10

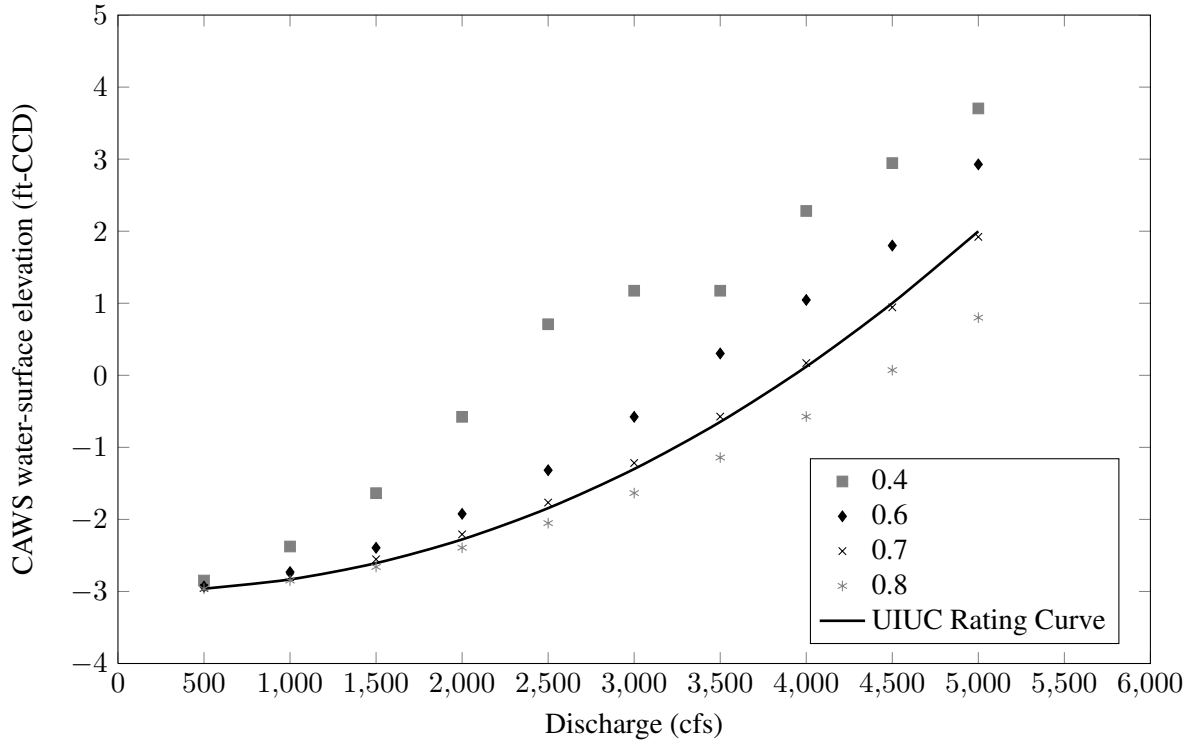


Figure 3.1: Submerged discharge coefficient for CRCW South Gates

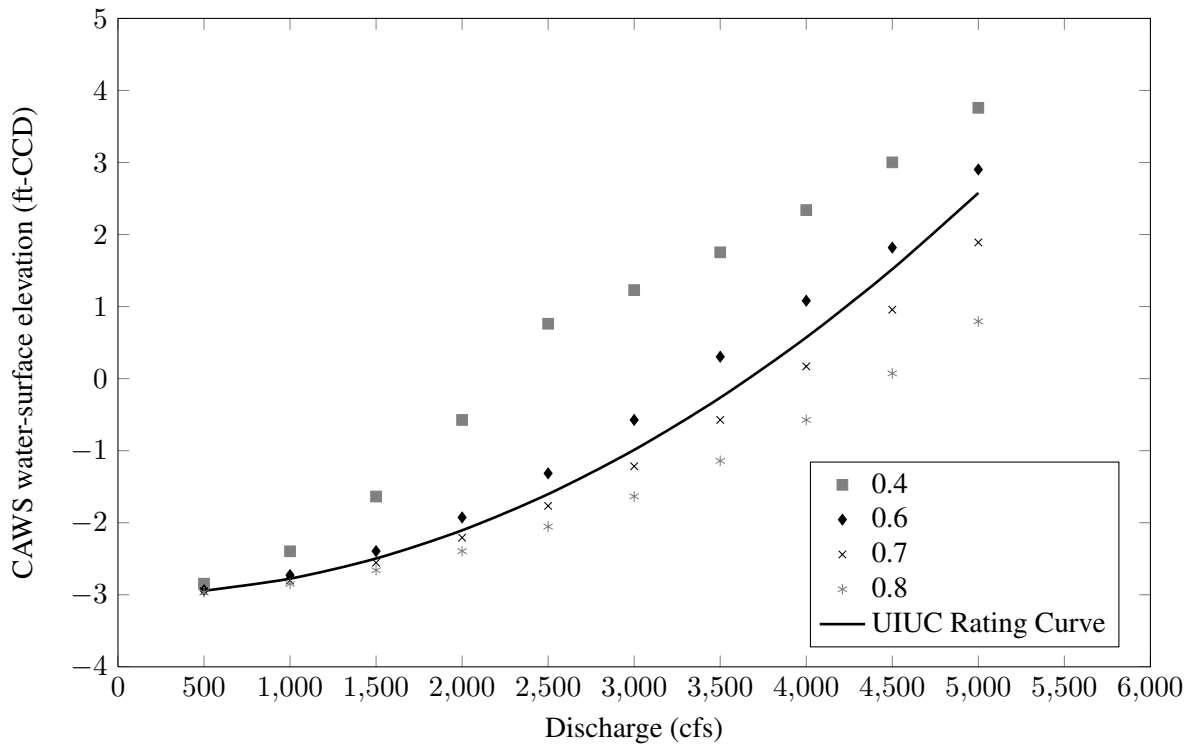


Figure 3.2: Submerged discharge coefficient for CRCW North Gates

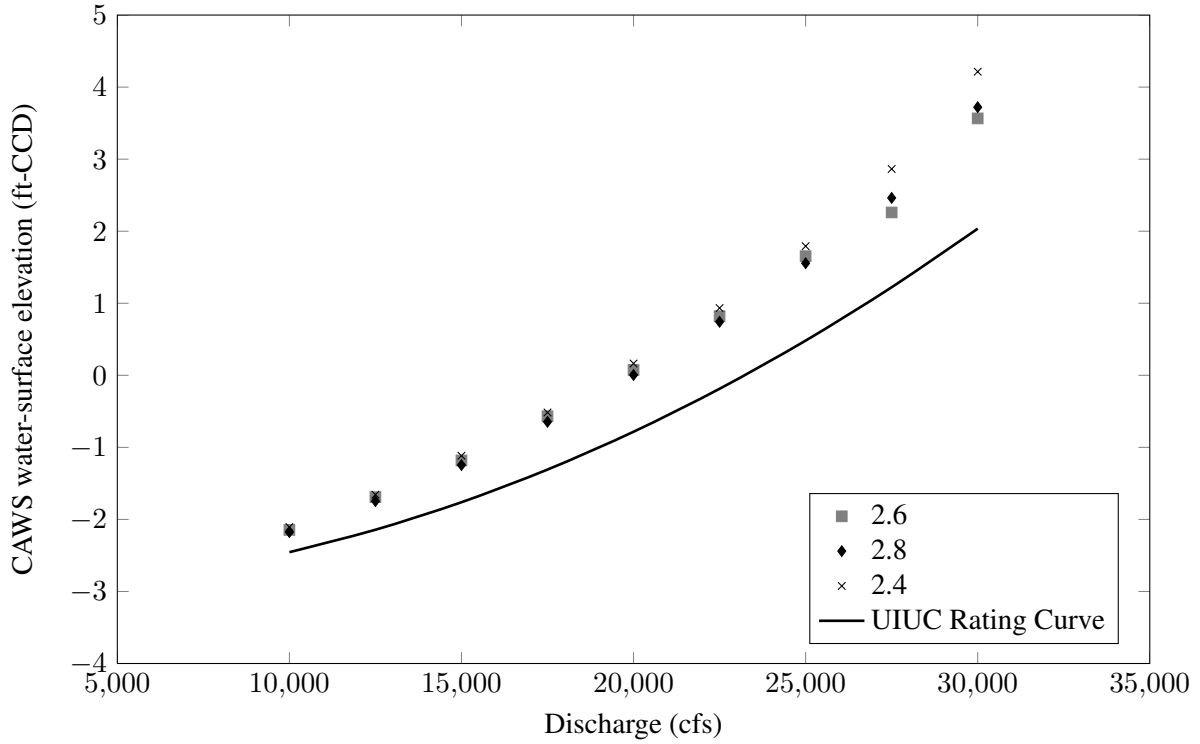


Figure 3.3: Discharge coefficient for CRCW Sector gates (Lock)

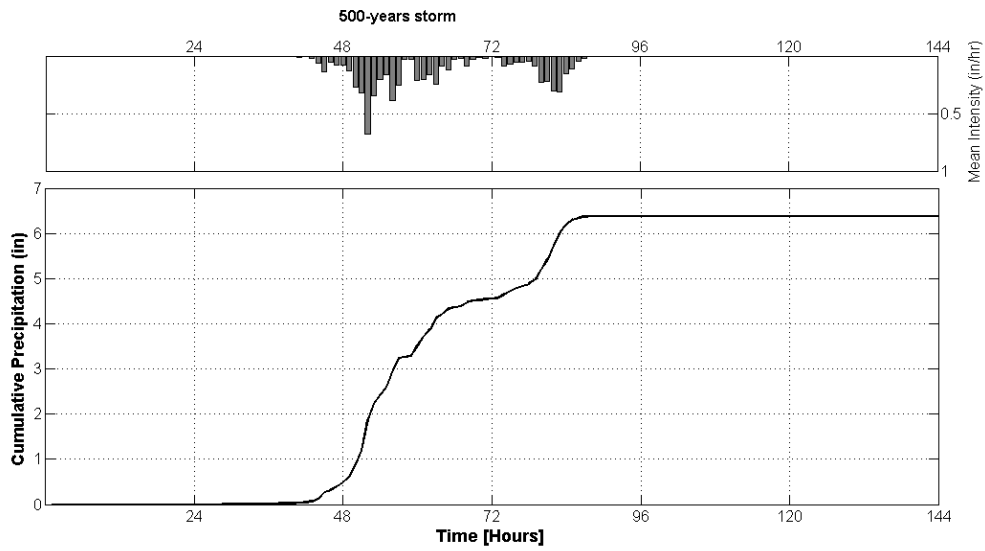


Figure 3.4: Intensity and cumulative precipitation 100-years storm

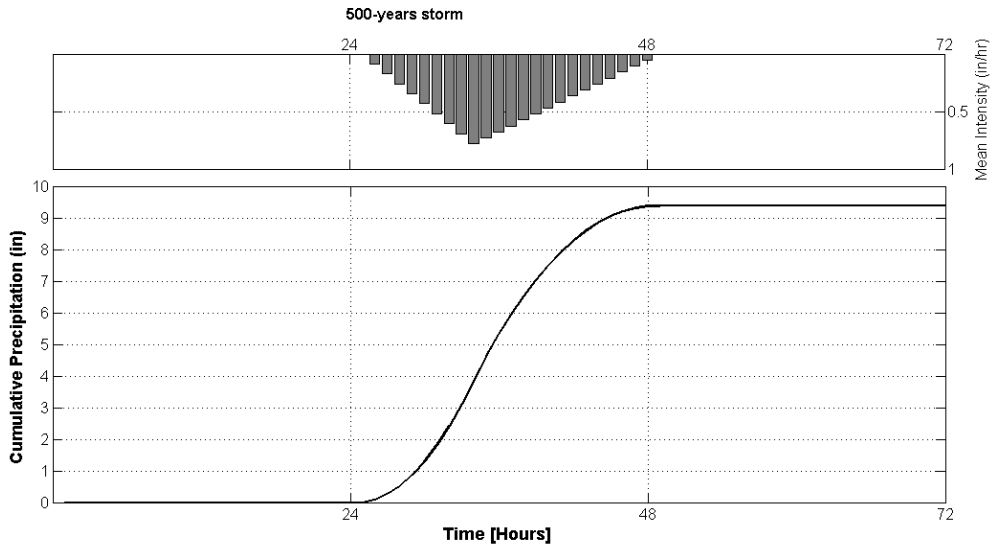


Figure 3.5: Intensity and cumulative precipitation synthetic 500-years storm

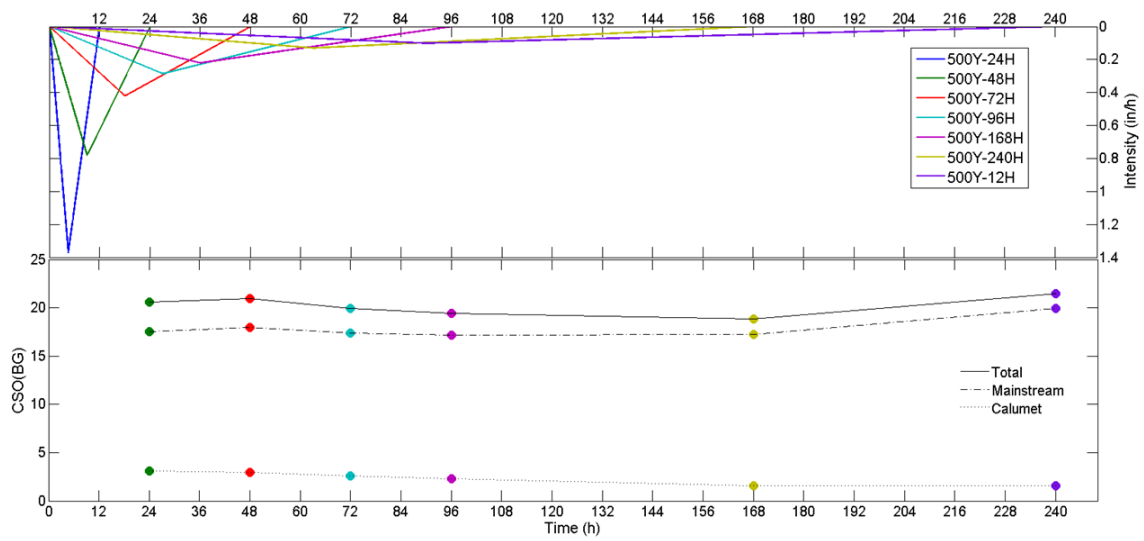


Figure 3.6: 500-years storms of different durations and corresponding volumes of CSOs

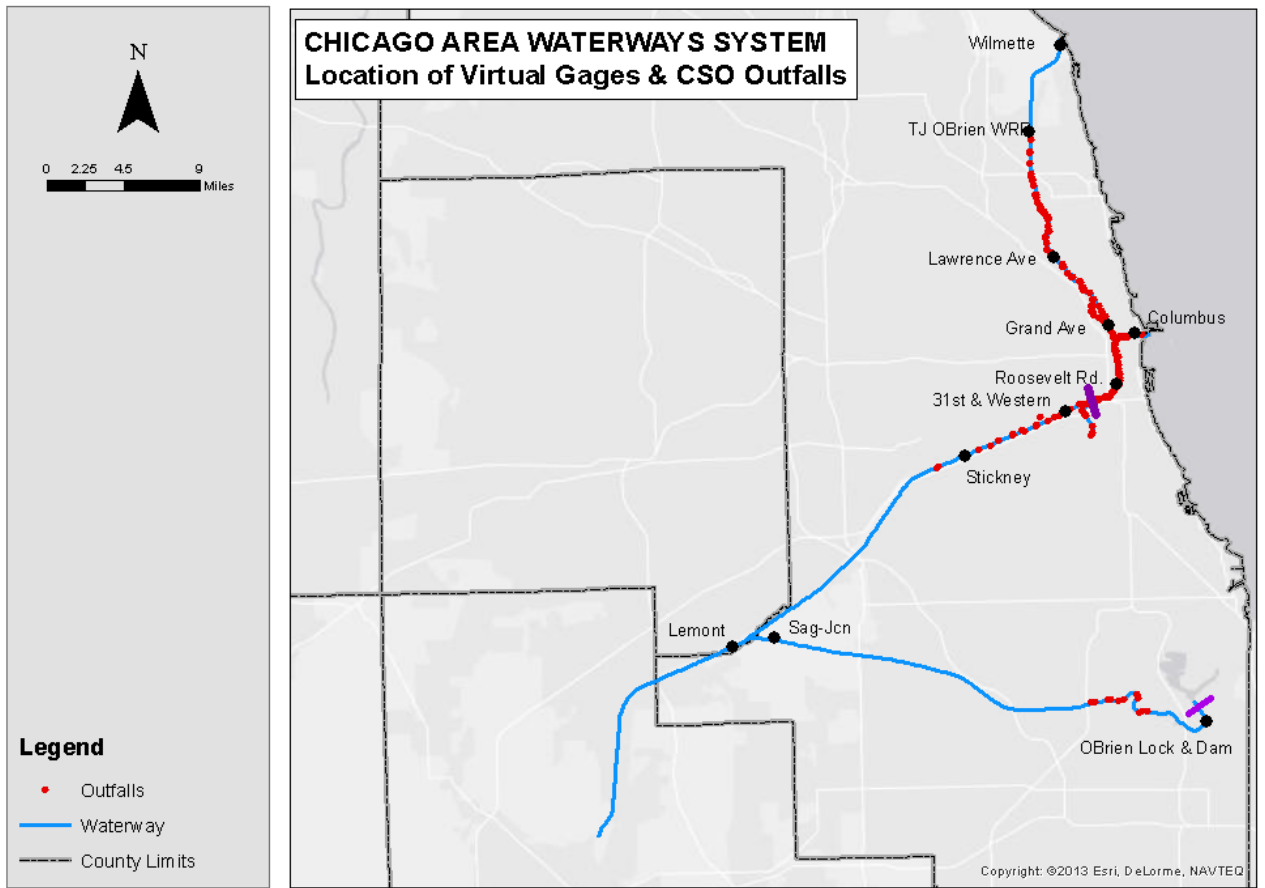


Figure 3.7: Location of monitoring virtual gage stations

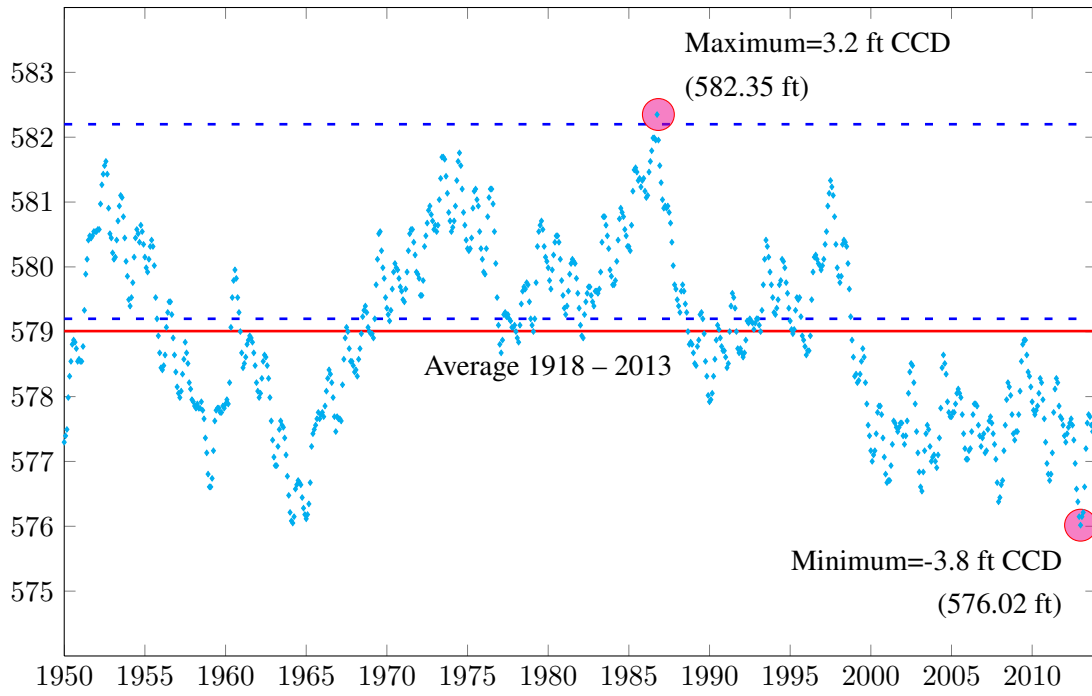
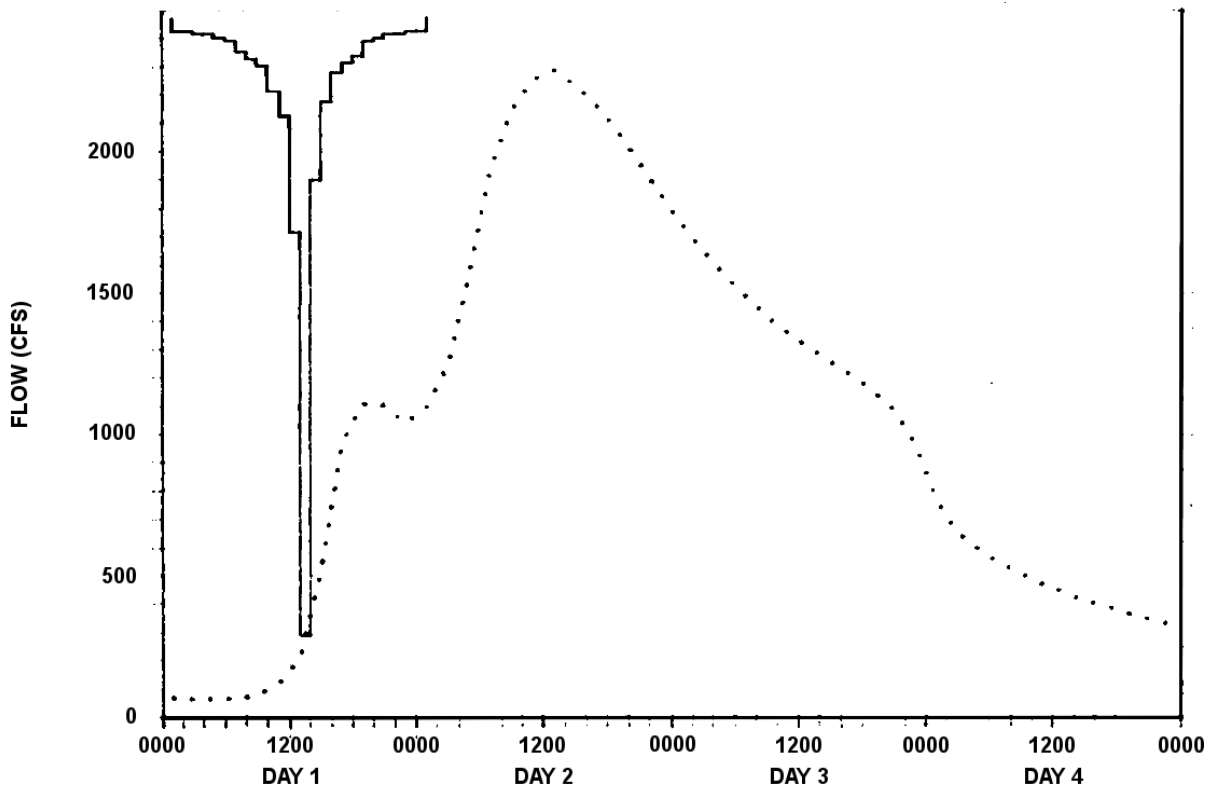


Figure 3.8: Lake wide monthly averaged water level - Lake Michigan from 1950 - 2013



..... FLOW AT HART DITCH
 _____ 100 YR (24H) HYETOGRAPH

Figure 3.9: Diversion hydrograph with mitigation structure in Little Calumet for 100-years (Source: US-ACE, 1990)

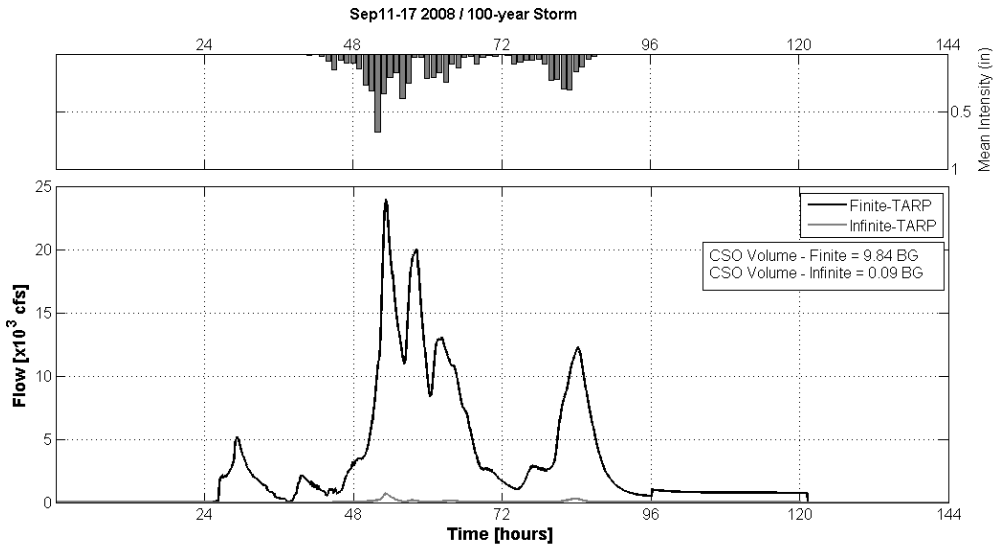


Figure 3.10: CSO hydrograph for 100-years storm with Finite- and Infinite- TARP capacity

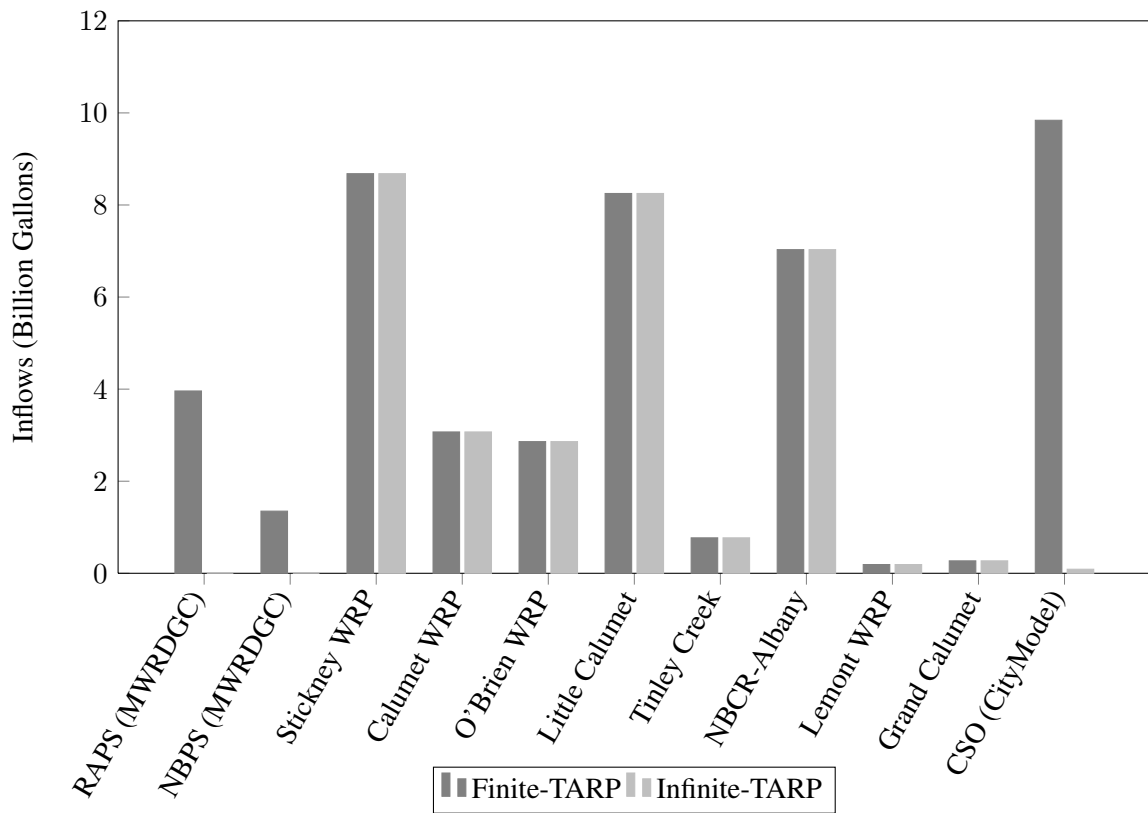


Figure 3.11: Volumes of water drained into CAWS during 100-years storm event for finite-and infinite-TARP capacities

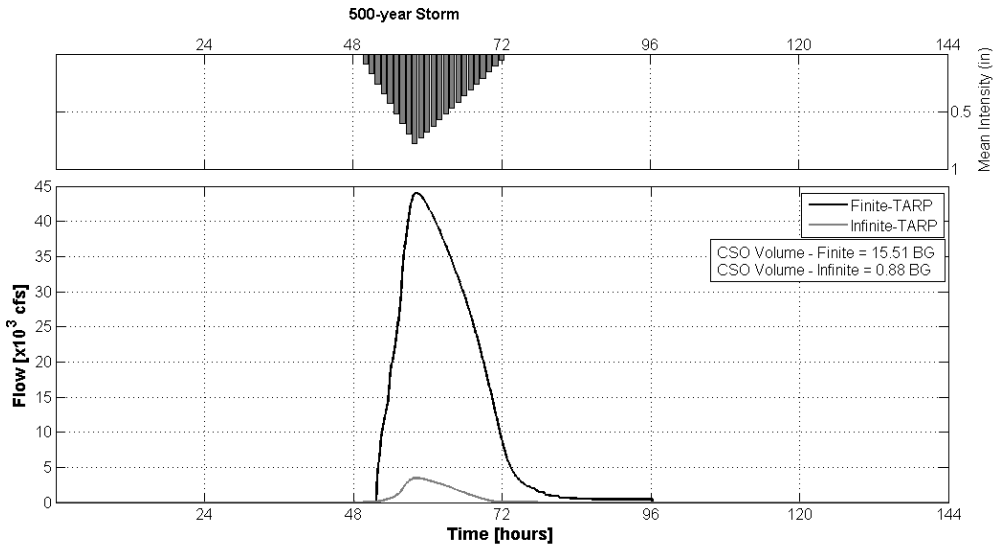


Figure 3.12: CSO hydrograph for 500-years storm with Finite- and Infinite- TARP capacity

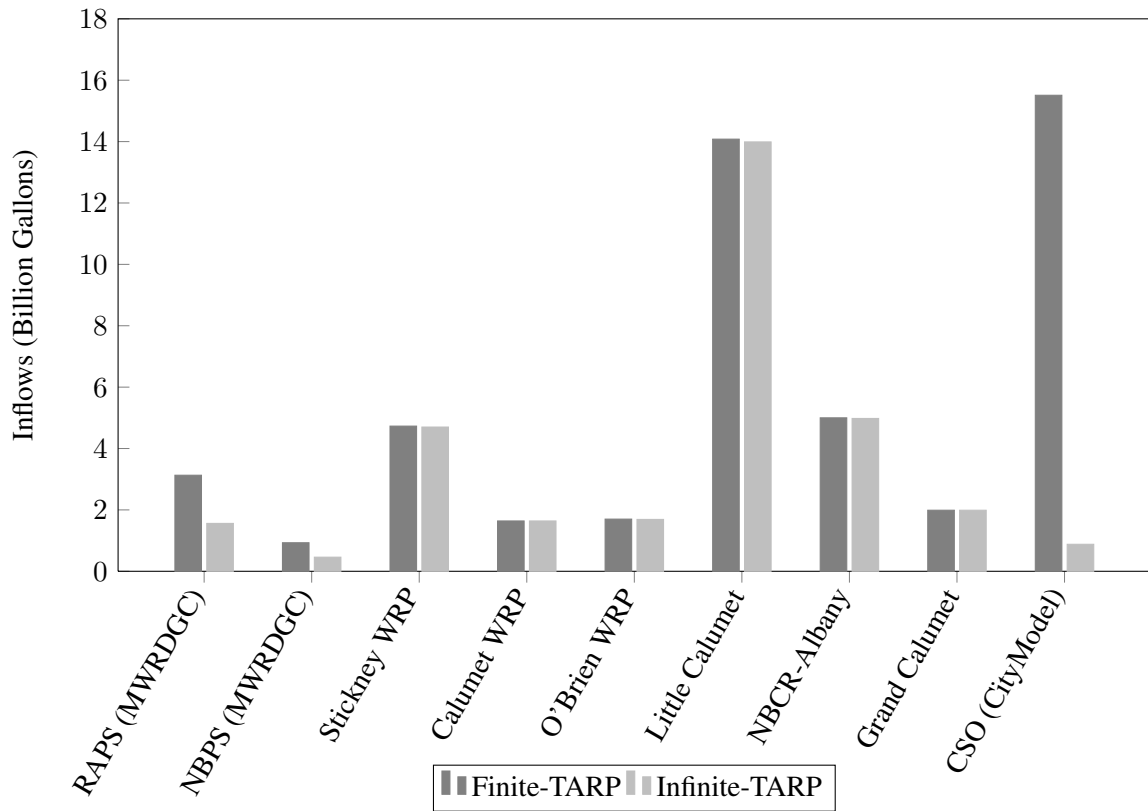


Figure 3.13: Cumulative CSO hydrograph for Finite- and Infinite-TARP capacities for 500-year storm events

4 Results

In general, the effect of the barriers and the new operational paradigm (lakefront gates permanently fully open) do have important consequences on the water levels in CAWS. With the South Branch Barrier the possibility of controlling water levels from Lockport would be lost on the lakeside of CAWS. Instead, Lake Michigan becomes a dominant factor on the water levels, particularly close to the controlling works (Wilmette Pumping station, Mainstem). If an extreme storm hits the City when Lake Michigan level is high (around +3 CCD) there is a major risk that submerged outfalls will not be able to discharge CSO into CAWS and that flow back-ups occur in the sewer pipes. Also reversal volumes would be increased in the presence of the barriers because any CSOs from outfalls and pumping stations, effluents from OBrien WRP, and inflows from North Branch would be evacuated through the lakefront gates.

On the Lockport side of the barriers flow discharges are reduced in presence of the barriers. In that case the upper reach of the CSSC would basically convey only CSOs from Racine Avenue Pumping Stations (RAPS), down to Stickney WRP. On the Cal-Sag and Calumet River branch, Little Calumet River is the most important inflow into CAWS. Because of the reduction of the discharge in CSSC, peak levels are lower at the Cal-Sag Junction and the Cal-Sag Channel has enough conveyance capacity for draining the water towards Lockport with no significant variations on peak water levels at OBrien Lock & Dam, except for the condition 500-year storm with Finite-TARP, and lake level at +3 CCD.

4.1 100-year storm event

4.1.1 Lake Michigan at 0 CCD and Finite-TARP capacity

With Lake Michigan at 0 CCD and a limited storage capacity of TARP, water levels are higher without the barriers as the available volume on the canals are used for storing CSOs and minimize flow reversals to Lake Michigan. This is the reason that water levels at Wilmette and Columbus are slightly above their corresponding critical levels with barrier (Figure 4.2 and 4.3); once the gates at lakefront are open the levels in CAWS are drawdown (level at Lake). With the barriers, on the other hand, CAWS levels are imposed by Lake Michigan and therefore remain higher than without the barrier for “dry” conditions.

Peak flow discharge at Columbus Dr is reached earlier on the case with barrier because the water flows directly to Lake Michigan; also it takes longer for evacuating the flow from the CAWS to the Lake since there is a smaller head difference. On the other hand, the case with no barrier has a delayed maximum peak flow because there is an available storage volume in the CAWS that has to be filled before opening the lakefront gates (Figure 4.2). The case with no barrier is similar to a “flush” operation, and pre-storm normal conditions are recovered faster.

Maximum water levels are reached in Lawrence Ave for both cases with and without the barrier. In fact the responses to the storm on water levels and flow discharge are very similar on both scenarios. Figure 4.3 shows that after the first storm-peak (+48 hours) both hydrographs come very close until the storm passed (about 80 hours). These similarities are because at this location the conditions at North Branch are dominant over Lake Michigan levels. These results however may be overestimated by the model. From historic data, the maximum observed water levels at Lawrence are around +5.0 CCD. As the flow is conveyed south towards Wolf Point or north towards Wilmette PS, the differences on water levels gets larger (compare for instance Figure 4.3 and 4.1).

On the south side of CAWS, at OBrien Lock & Dam model results have similar water levels and flow discharges with and without barriers (Figure 4.4). Even for the No Barrier scenario water does not reach the critical levels for opening the sluice gates (+3.5 CCD).

4.1.2 Lake 0 CCD and Infinite-TARP capacity

In Figure 3.10 it was showed that CSOs are drastically reduced with Infinite-TARP condition. Although CSOs from storm events have some effect on water levels in CAWS, it is not enough to raise them up to critical values near the lakefront. In general, maximum water levels are higher without the barrier as CAWS storage capacity is used, but in none of the scenarios the critical level was exceeded at the controlling works.

Since critical levels were not reached near the lakefront, there was no reversal flow at all for the case without barriers: all the water from the storm was stored in TARP and the canals or evacuated through Lockport Powerhouse. On the other hand, with the barrier the lakefront remains open and there are flow reversals to the Lake on CRCW and Wilmette that sum up 5.9 BG (Figure 4.5 and 4.6). At OBrian Lock & Dam water levels are not affected by the presence of barriers and no discharges to Lake Michigan occur (Figure 4.7). Spikes at initial time of hydrographs are attributed to numerical instabilities during the model warm up period.

4.1.3 Lake +3 CCD and Finite-TARP capacity

A more critical flooding scenario is with high water levels in Lake Michigan. A value of +3 CCD is close to historic maximum and to critical levels of CAWS before reversal flows occur under current operation. As mentioned before, the level of the Lake becomes a boundary condition for the CAWS when the gates at lakefront are open. With the barriers it implies that, on the lakeside, water level at CAWS remain near +3 CCD, and higher when the storm hits. On the Lockport side of the barrier, the barrier limits the CSO flow and the water levels and flow discharges at CSSC and Cal-Sag Channel are lower than without the barriers.

At Wilmette and Columbus Dr. the differences on maximum water levels with and without barriers are

small once the storm hits and the controlling works are open Figure 4.8 and 4.9. Lawrence Ave., near the confluence with North Branch, is a critical point because of inflows from this tributary, and because it is far enough from the lake front. Estimated maximum water levels exceed +8 CCD when barrier is in place, and would be about a foot lower without barrier (Figure 4.10). The peaks are attenuated as they travel towards the Lake by Wilmette or CRCW.

When there is no barrier but Lake Michigan is high, once the gates are open and the reversal flows are flushed to Lake Michigan, Lockport Powerhouse becomes the only system outlet; thereby some flow at CRCW towards Lockport after the storm is observed (Figure 4.9).

Downstream of the north barrier, at 31st & Western (Figure 4.11) the flow discharges are limited to RAPS effluents during wet weather conditions. For example the maximum peak of +5,000 cfs corresponds to the maximum capacity of RAPS; but when there are no CSOs the flow discharge is null ($t < 48$ Hrs; $t > 120$ Hrs). Without the barrier, given a Lake Level of +3 CCD, levels are controlled by Lockport Powerhouse until the storm hits and critical levels are reached at Wilmette and CRCW; then lakefront gates are permanently open and water level is drawdown. But once the storm is over, since the gates remain open, the water flows from Lake Michigan into CAWS. The water level stabilizes above +2 CCD at 31st & Western, with a flow discharge close to 9,000 cfs driven by the head difference between Lake Michigan and Lockport Powerhouse (Figure 4.11).

At OBrien Lock & Dam, the water level with the barrier is higher than with the barrier, but still does not reach critical values for gate opening. Discharges with the barrier in place are null (Figure 4.12).

4.1.4 Lake +3 CCD and Infinite-TARP capacity

If large enough storage is available at TARP when the storm hits, water levels are not largely affected by the storm in any case. This is observed in relatively small variations of water levels during the simulation periods at different locations (Figure 4.13 to 4.16). On the lakeside of the barrier water levels are increased by the barrier, because the gates remain open for a high Lake Michigan; notice that elevations at these locations remain above +3 CCD when barrier is in place. Without the barrier water levels are controlled from Lockport.

With the barrier water level at Columbus Dr. is basically fixed by Lake Michigan (+3 CCD) for the entire simulation period (Figure 4.13). Without barriers, the water level at Columbus is controlled from LPPH, and stays close to -2 CCD. The slight increase of the level on the latter case is due mainly to inflows from North Branch. At Lawrence Ave. the effect of the storm seems to be more important on water levels and flow discharge (Figure 4.14). This is explained in great manner because is the closest location to the North Branch confluence.

Downstream of the north barrier, on 31st & Western Ave, there are no big differences between maximum water levels when the barrier is in place (Figure 4.15). However the flow hydrographs are very different: without the barrier all the water on the lake side of the barrier goes through this location towards Lockport with North Branch as major tributary; but with the barrier the only source is RAPS during wet conditions. At OBrien Lock and Dam critical water levels for flow reversals are not reached in any case. With the barrier water levels goes slightly down, probably because the water level at the junction goes down as the discharge from upstream of CSSC is limited (Figure 4.16).

4.2 500-year storm event

4.2.1 Lake +3 CCD and Finite-TARP capacity

The 500-year storm was represented by a single synthetic event of 24 hours duration (Figure 3.5). As expected higher water levels and flow discharges were significantly higher than for the 100-years event for both with and without barrier. The relative effect of the barrier on water levels varies along the CAWS: on northern stations (Wilmette and OBrien WRP) and downstream of the north barrier (31st, Stickney, Lemont, and OBrien L&D) the water levels are higher when the barrier is in place; but the opposite is observed closer to Downtown area (Grand Ave, Columbus Dr, and Roosevelt Rd.). At Lawrence Ave. computed maximum water elevations are close to full bank levels for both cases.

In Columbus Dr. (Figure 4.17) the maximum water levels estimated with the model are +4.4 CCD (583.61 ft) without barriers, and 4.1 CCD (583.28) with barriers. The respective peak discharges (towards the Lake) are about -23,000 cfs and -24,000 cfs. Once the storm is over, water levels dropdown close to +3 CCD as in Lake Michigan. Because without the barrier the gates stay fully open Lake Michigan diverts some flow into CAWS (about 10,000 cfs) after hour 96.

Lawrence Ave. once again presents the highest water levels: +10 CCD without barrier and +11.3 CCD with the barrier in place (Figure 4.18). Both levels presumably are very close to full-bank levels by Lawrence Ave. Therefore, although the barriers do increase water levels at this location (+1.2 ft), the 500-years storm its a very high demand for the conveyance capacity of CAWS, disregarding the presence of the barrier.

In Wilmette PS the barrier raises up the peak levels by 0.70 ft with respect to the scenario without barrier (Figure 4.19). The flow discharges to Lake Michigan are relatively high and similar for both cases (5,000 cfs). After hour 72, the flow becomes negligible.

Downstream of the north barrier, by 31st & Western, water levels are very similar before the storm, then the maximum level (+5.6 CCD) is reached earlier without the barrier, but its lower than the peak level for the case with barrier (+6.8 CCD) (Figure 4.20). However, the maximum discharge for the no barrier case (13,000 cfs) is much higher than the peak flow with the barrier (6,000 cfs). This is because initially all

CAWS is draining exclusively towards Lockport until the lakefront gates are open. Once the barrier is in place the main flow source at this location is RAPS which capacity is +5,000 cfs.

By OBrien Lock & Dam the presence of the barrier increases the water level close to +7 CCD. Without the barrier water levels are kept below +3.5 CCD by operating the gates. The flow hydrograph also reflects the effect of this operation with a maximum flow discharge to Lake Michigan of -7000 cfs right after the storm most intense hour (Figure 4.21).

4.2.2 Lake +3 CCD and Infinite-TARP capacity

In general the presence of the barrier increases maximum water levels in CAWS, particularly in downtown area (Grand Ave, Columbus, and Roosevelt Ave.). On the lakeside of CAWS for “dry” conditions water levels remain higher because of the level of Lake Michigan (Figure 4.22 to 4.24).

On the Lockport side of the barrier there is a reduction on the CSO with the barrier since it is limited to effluents from RAPS and WRP, which are relatively low for Infinite-TARP condition.

At Columbus, critical levels are not reached in any case. However, because of the presence of the barrier about 5.6 BG would be sent to Lake Michigan. Without the barrier Lockport controls the water levels and there are no flow reversals (Figure 4.22).

Similar maximum water levels are estimated at Lawrence Ave (+5 CCD). With the barrier in place and lakefront open the levels remain above +3 CCD. This means an increased vulnerability of the system for backing up flows through pipes into basements and lower areas on part of the city. Without the barrier Lockport effectively controls the water level during dry and wet conditions for the Infinite-TARP condition. Discharge hydrographs are quite similar and affected mainly by inflows from North Branch (Figure 4.23).

At Wilmette PS maximum water level is slightly higher without the barriers because is governed by the operation of the gates and a volume of CSO is released into Lake Michigan (0.1 BG). However, with the barrier in place water levels are higher during a longer period of time, and a larger volume of water is released to Lake Michigan (about 1.9 BG) (Figure 4.24).

On the Lockport side of the barrier at 31st & Western and OBrien Lock & Dam (Figure 4.25 and 4.26) maximum water levels are not greatly affected. Flow discharges are systematically reduced as the flow from North Branch, NBPS, and other CSO would flow into Lake Michigan rather than through Lockport.

4.2.3 Mitigation works

The effect of diverting part of the flow from Little Calumet River (LCR) to Lake Michigan was considered for both 100- and 500-years 24 hours scenarios with barriers and Finite-TARP. The flow hydrograph for Little Calumet River was reduced by a factor of 0.4 to account for the flow diversion by mitigation works.

For the 100-year event without the mitigation works, water surface do not reach critical levels required for gate opening at OBrien Lock & Dam (Figure 4.27). On both cases discharges to Lake Michigan are null. At the Sag-Junction it is interesting to see that water levels with mitigation works (i.e. reduced discharge) are slightly higher than without the mitigation, although both have a maximum water level of -1.45 CCD (Figure 4.28). This is explained by the way Lockport sluice gates are operated: For higher discharges (no mitigation works) lower levels at Lockport are required to gain enough hydraulic head for conveying a larger flow discharge and keep water levels below targets; thereby gate openings are larger and longer for the case without mitigation. Notice that this is not observed at OBrien Lock & Dam, where the mitigation works would reduce water levels as expected.

For the 500-years case, the critical level at OBrien Lock & Dam is exceeded by 3 ft for (20% of time), primary due to flows from LCR. By applying a reduction factor to LCR hydrograph the flow peak is reduced from 6,700 to 2,700 cfs. Consequently, the peak water level drops by 1.9 ft (new max. 4.8 CCD). Critical level would still be exceeded but for a shorter period (10% of time). By the Sag-Junction mitigation water levels closely follows OBrien Lock & Dam because of pool formed by the barrier (Figure 4.29 and 4.30).

4.3 Fraction of time critical levels are exceeded

A complimentary analysis to the time series is presented in this section. The main purpose of the analysis is to find what fraction of time that critical levels in CAWS are exceeded with and without the barriers. Mainly because higher water levels for longer periods imply higher probabilities back up flows in the sewer system caused by submerged outfalls. Cumulative Frequency Distributions (CFD) of the simulated water levels were used for this purpose. Then, the fractions of time of exceedance of critical levels for different scenarios at each location were summarized on the bar graphs presented below.

Close to the lakefront the probability of exceeding critical levels is lower than for stations in inner locations. For the 100-year storm at Columbus Dr. critical level is not exceeded as the CRCW gates have enough capacity for controlling water levels; at Wilmette PS critical levels are only exceeded for +3 CCD and Finite-TARP (1% of simulation period) (Figure 4.31). For the 500-year storm, only at Wilmette PS there is a significant fraction of time over critical levels, although less than 10% for both Finite- and Infinite-TARP cases.

Closer to the South Branch Barrier, at Roosevelt Rd water levels without barriers were higher than with

barriers only for Lake at 0 CCD and Finite-TARP (Figure 4.32). This is because in that case a larger flow discharge is conveyed towards Lockport than once the barrier is in place. However, for high levels at Lake Michigan (+3 CCD) CAWS behave as a pool; thereby water level remains above critical at that station during the entire simulation. The barrier aggravates this condition by increasing the probability from 0.63 to 0.99 when Lake is +3 CCD. However, with Infinite-TARP critical levels are not exceeded.

At Lawrence Ave. water surface also stays for a considerable fraction of time above critical elevation. The effect of the barrier is more evident for the case Finite-TARP, Lake level 3 CCD, and 100-year storm. For those conditions the fraction of time above critical levels is raised from 0.31 to 0.46 (Figure 4.33).

4.4 Figures and Tables

Table 4.1: Fraction of time that critical water levels are exceeded on the lakeside of South Branch Barrier, 100 year storm

Lake Level (CCD)	TARP	Barrier	Wilmette	Lawrence Ave	Grand Ave	Columbus Drive	Roosevelt Rd
0	Finite	Y	0	0.17	0	0	0
		N	0	0.18	0.04	0	0.1
	Infinite	Y	0	0	0	0	0
		N	0	0	0	0	0
3	Finite	Y	0.01	0.46	0.11	0	0.99
		N	0	0.31	0.04	0	0.63
	Infinite	Y	0	0	0	0	0.99
		N	0	0	0	0	0

Table 4.2: Fraction of time that critical water levels are exceeded on the Lockport side of South Branch Barrier, 100 year storm

Lake level	TARP	Barrier	31st & Western	OBrien Lock & Dam	Sag-Junction
0	Finite	N	0.6	0	0.27
		Y	0.11	0	0.03
	Infinite	N	0.66	0	0.07
		Y	0.6	0	0.02
3	Finite	N	0.98	0	0.63
		Y	0.64	0	0.03
	Infinite	N	0.98	0	0
		Y	0.64	0	0.03

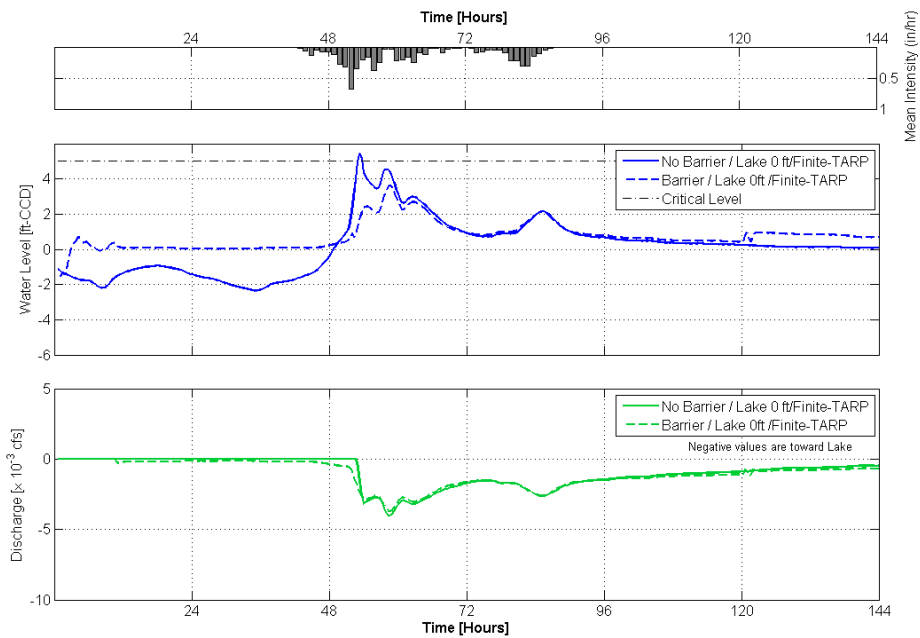


Figure 4.1: Effect of barrier on water level and flow discharge at Wilmette PS
Lake Michigan=0 CCD and Finite-TARP

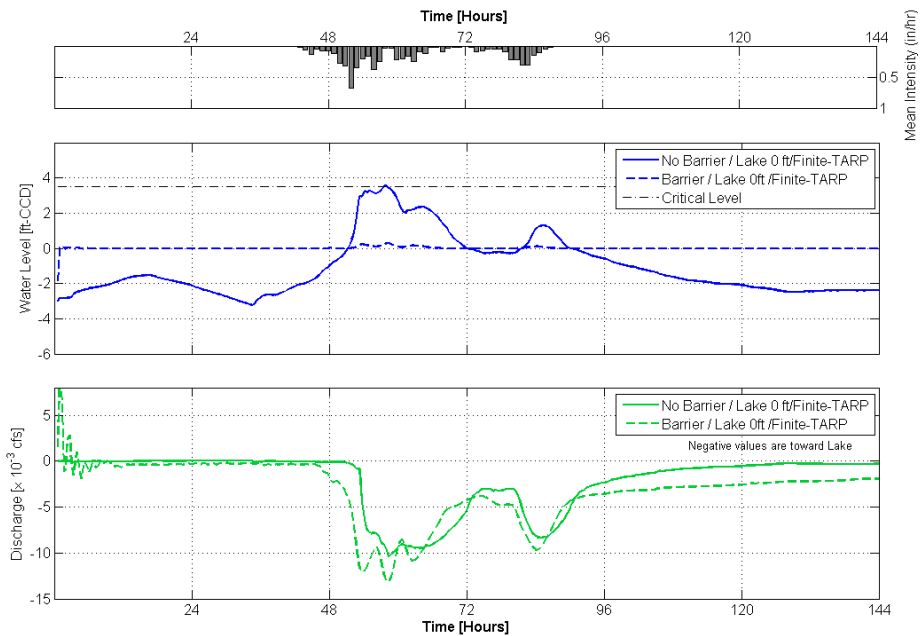


Figure 4.2: Effect of barrier on water level and flow discharge at Columbus Dr
Lake Michigan=0 CCD and Finite-TARP

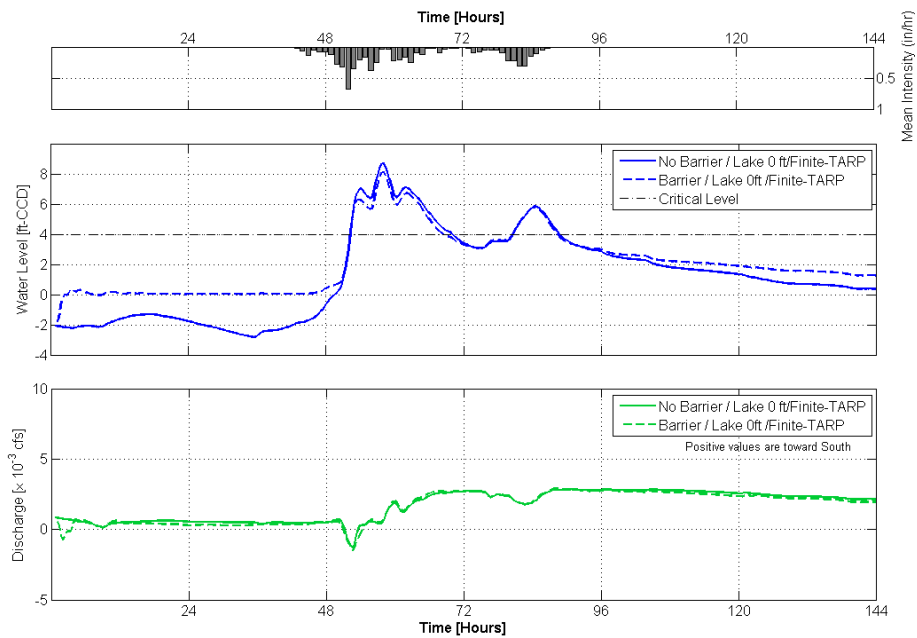


Figure 4.3: Effect of barrier on water level and flow discharge at Lawrence Ave
Lake Michigan=0 CCD and Finite-TARP

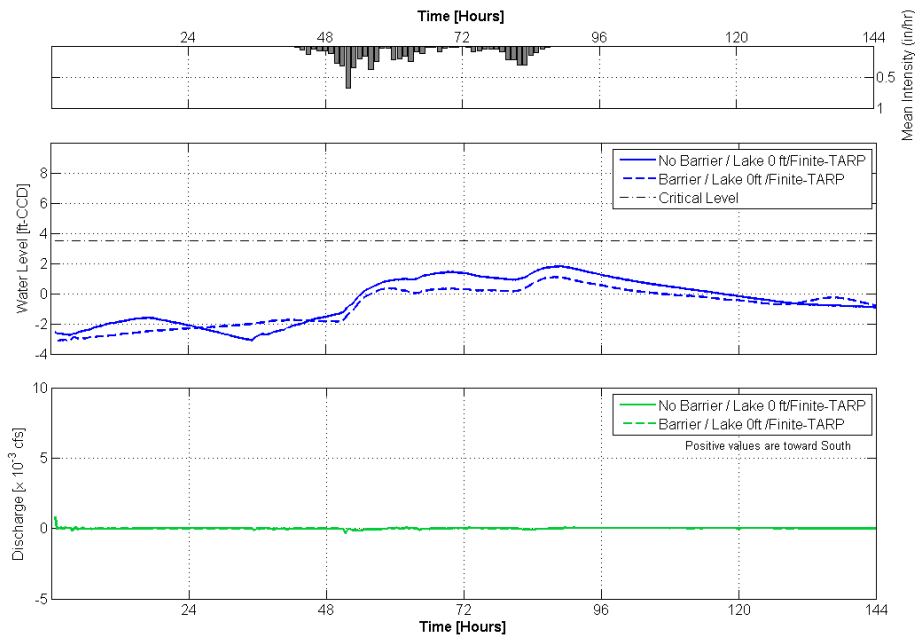


Figure 4.4: Effect of barrier on water level and flow discharge at O'Brien Lock & Dam
Lake Michigan=0 CCD and Finite-TARP

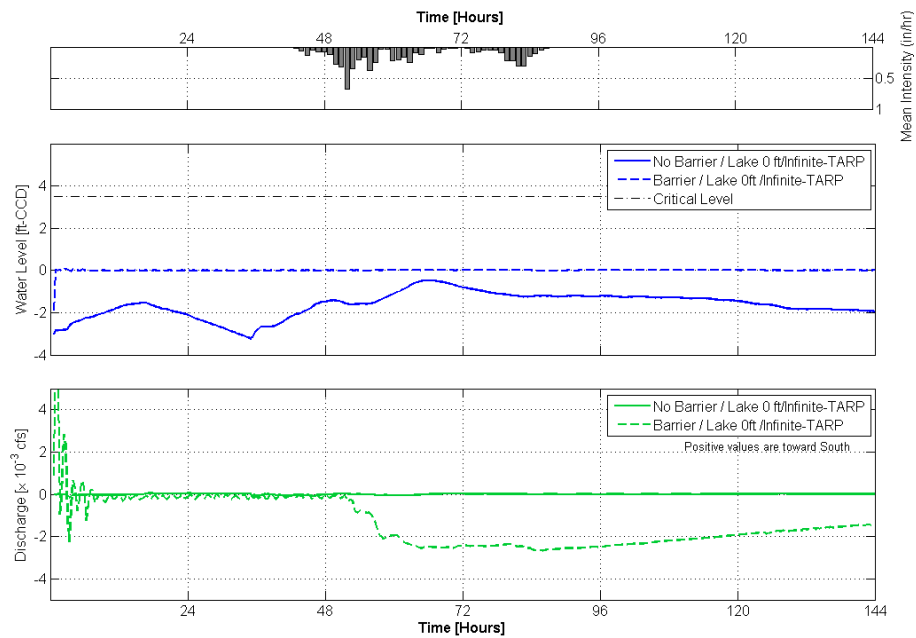


Figure 4.5: Effect of barrier on water level and flow discharge at Columbus Dr.
 Lake Michigan=0 CCD and Infinite-TARP

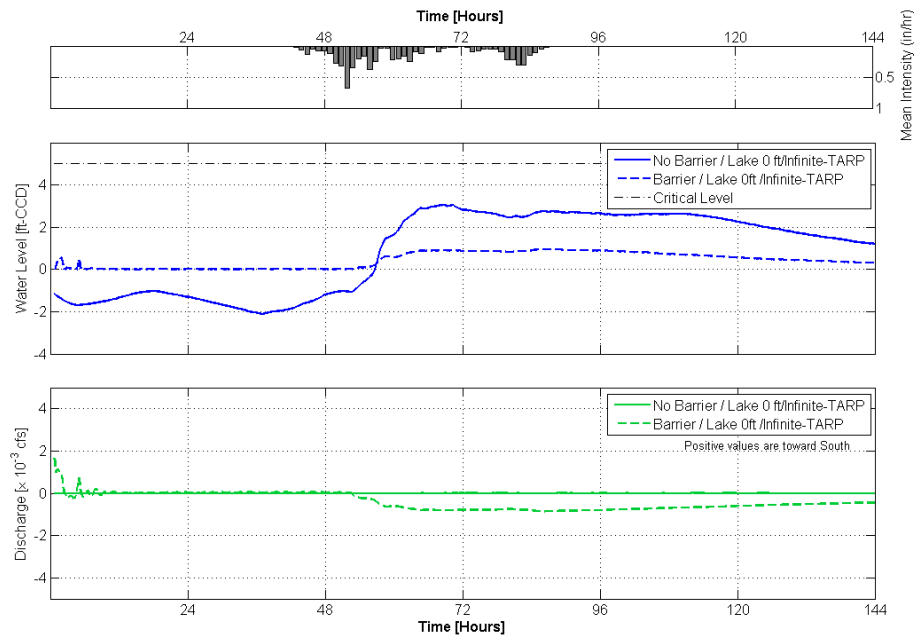


Figure 4.6: Effect of barrier on water level and flow discharge at Wilmette Pumping Station
 Lake Michigan=0 CCD and Infinite-TARP

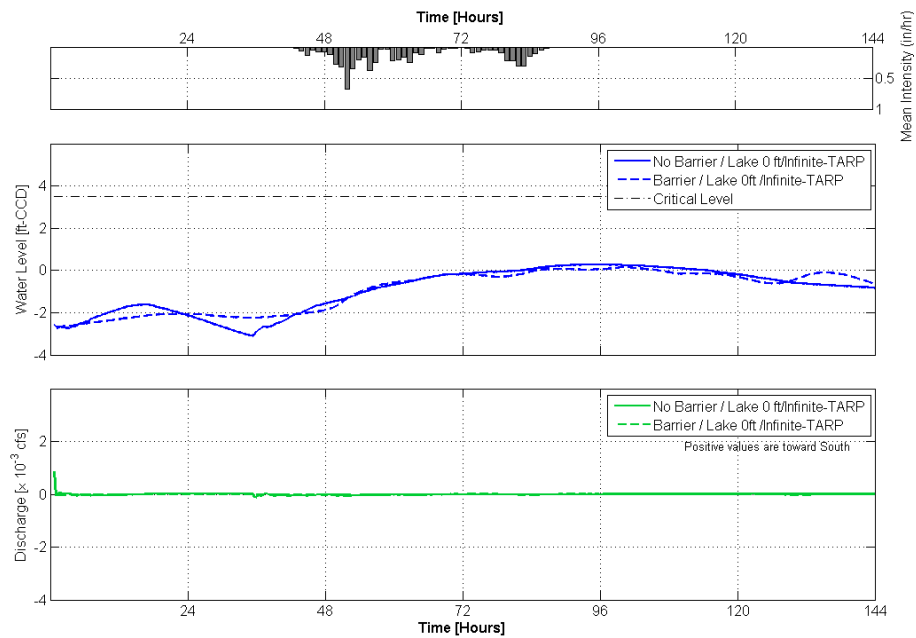


Figure 4.7: Effect of barrier on water level and flow discharge at O'Brien Lock & Dam
 Lake Michigan=0-ft CCD and infinite-tarp

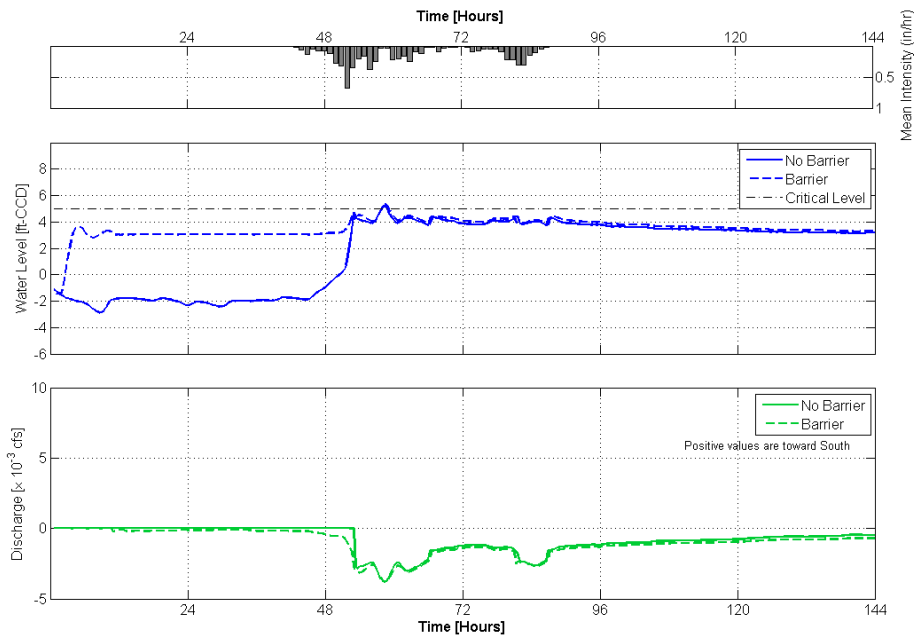


Figure 4.8: Effect of barrier on water level and flow discharge at Wilmette Pumping Station
 Lake Michigan=+3 CCD and finite-tarp

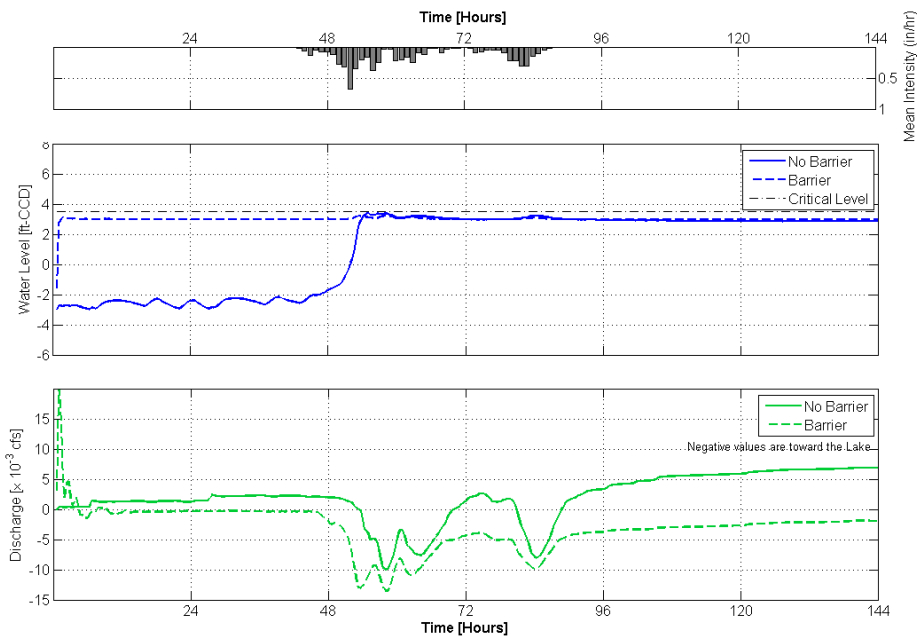


Figure 4.9: Effect of barrier on water level and flow discharge at Columbus Dr.
Lake Michigan=+3 CCD and finite-tarp

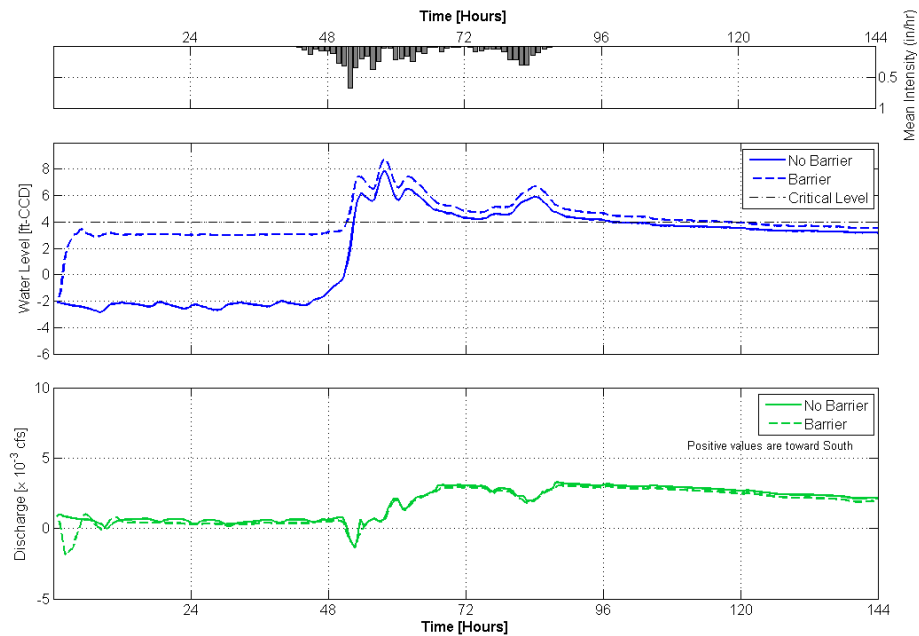


Figure 4.10: Effect of barrier on water level and flow discharge at Lawrence Ave.
Lake Michigan=+3 CCD and finite-tarp

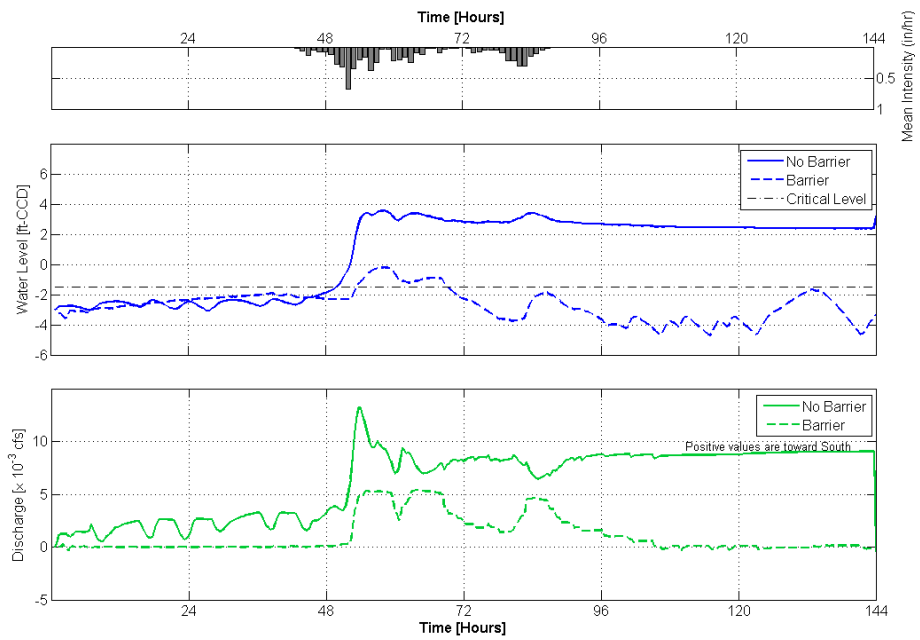


Figure 4.11: Effect of barrier on water level and flow discharge at 31st & Western (Lockport side of south branch barrier)

Lake Michigan=+3 CCD and Finite-TARP

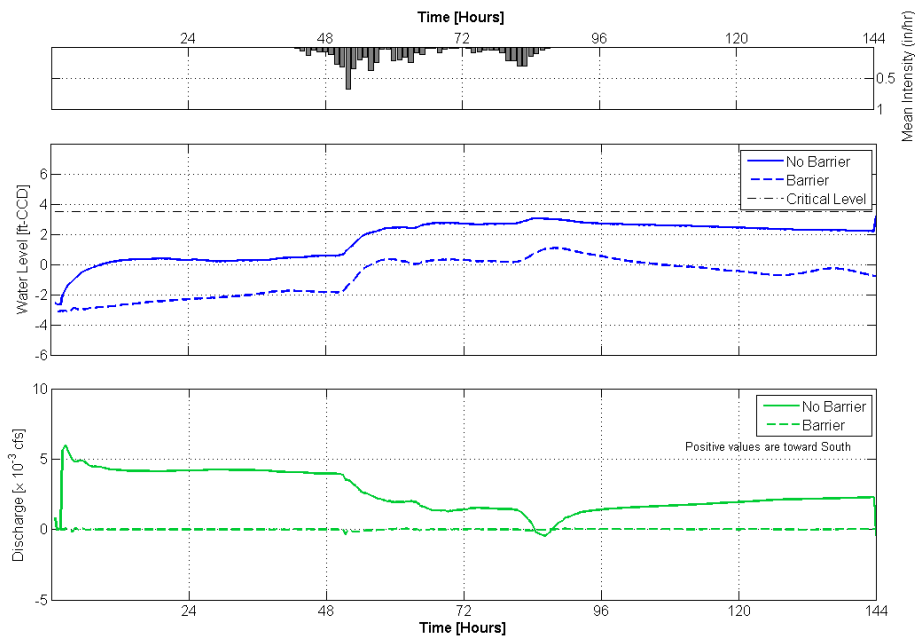


Figure 4.12: Effect of barrier on water level and flow discharge at O'Brien Lock & Dam
Lake Michigan=+3 CCD and Finite-TARP

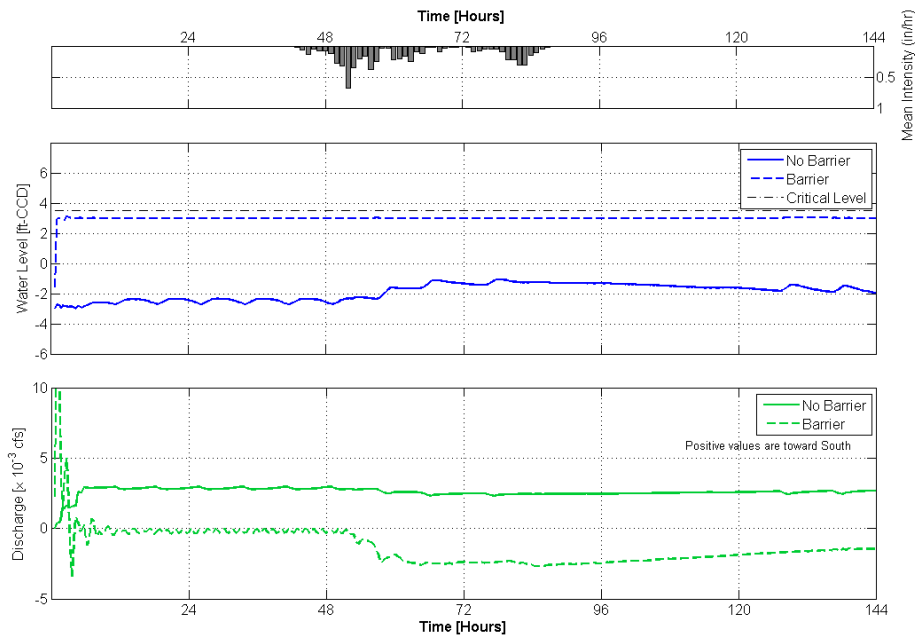


Figure 4.13: Effect of barrier on water level and flow discharge at Columbus Dr.
Lake Michigan=+3 CCD and Infinite-TARP

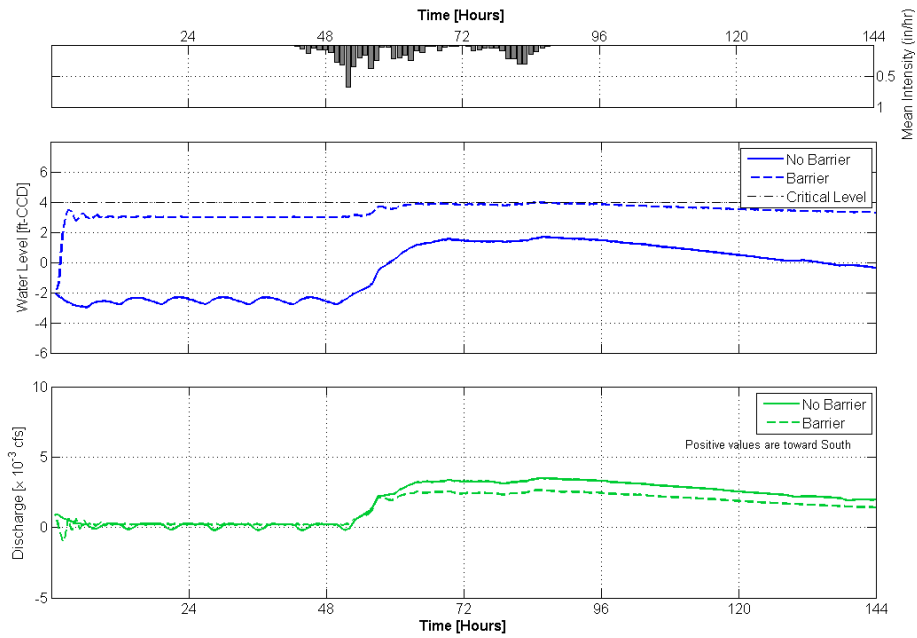


Figure 4.14: Effect of barrier on water level and flow discharge at Lawrence Ave.
 Lake Michigan=+3 CCD and Infinite-TARP

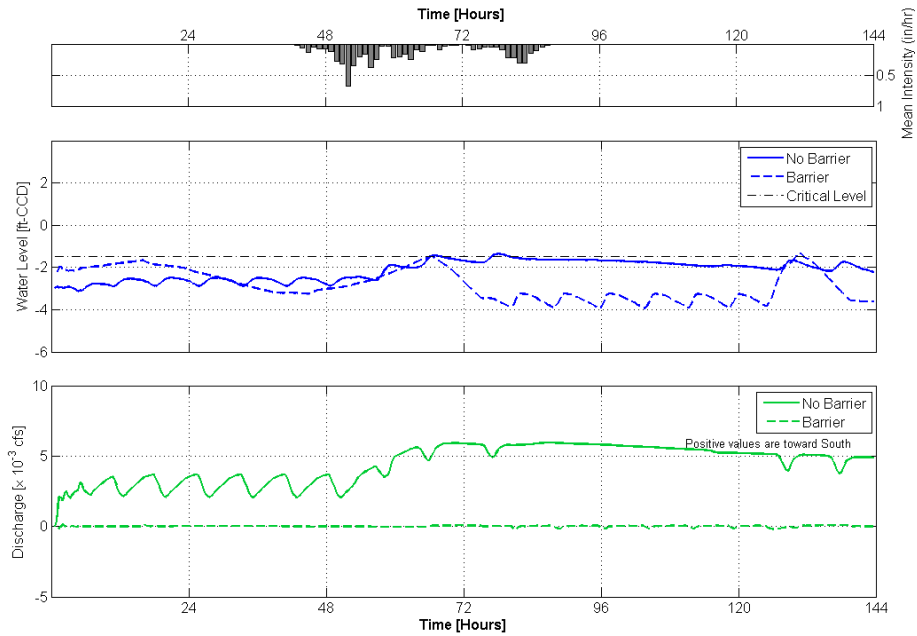


Figure 4.15: Effect of barrier on water level and flow discharge at 31st & Western.
 Lake Michigan=+3 CCD and Infinite-TARP

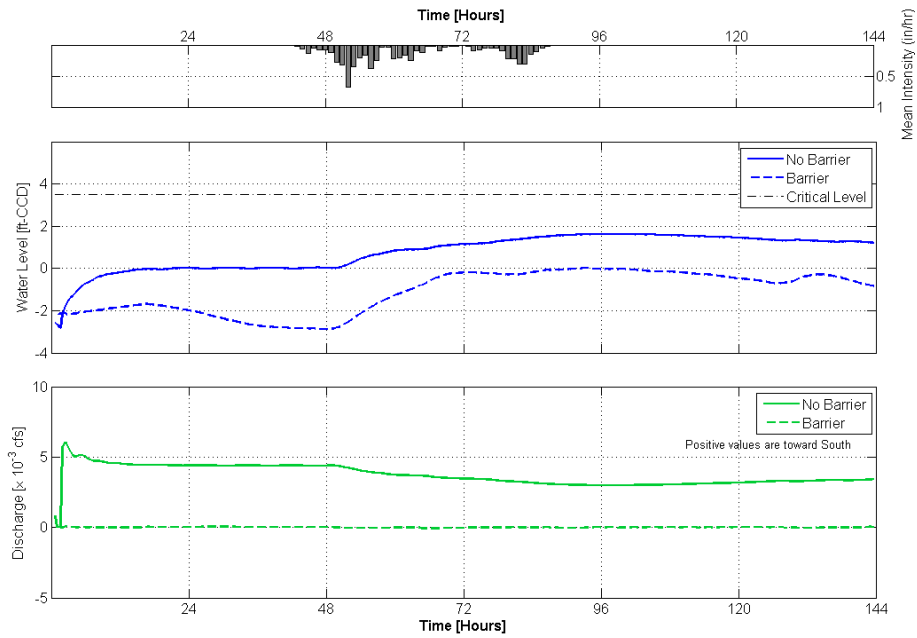


Figure 4.16: Effect of barrier on water level and flow discharge at O'Brien Lock & Dam.
 Lake Michigan=+3 CCD and Infinite-TARP

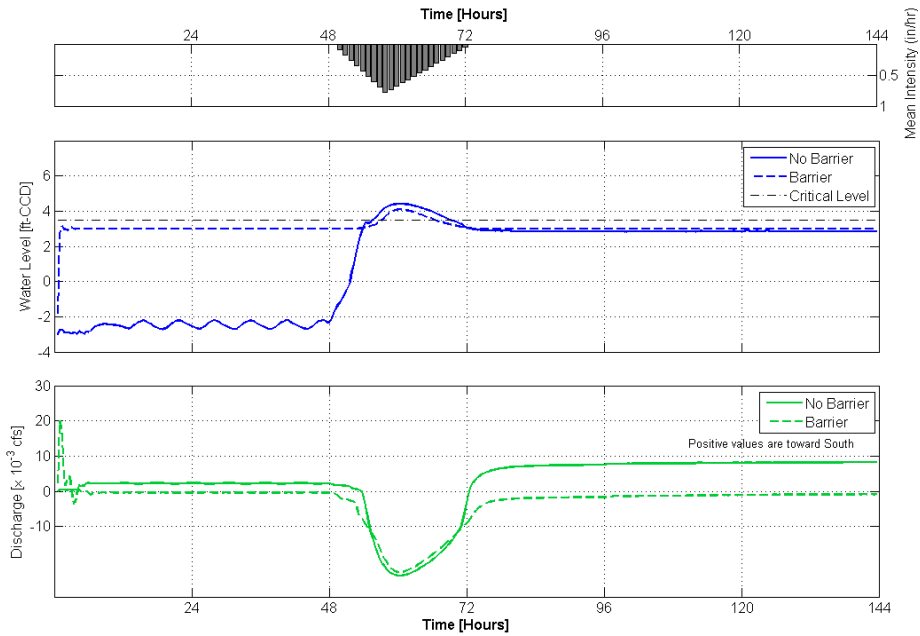


Figure 4.17: Effect of barrier at Columbus Dr. / 500-year storm.
 Lake Michigan=+3 CCD and Finite-TARP

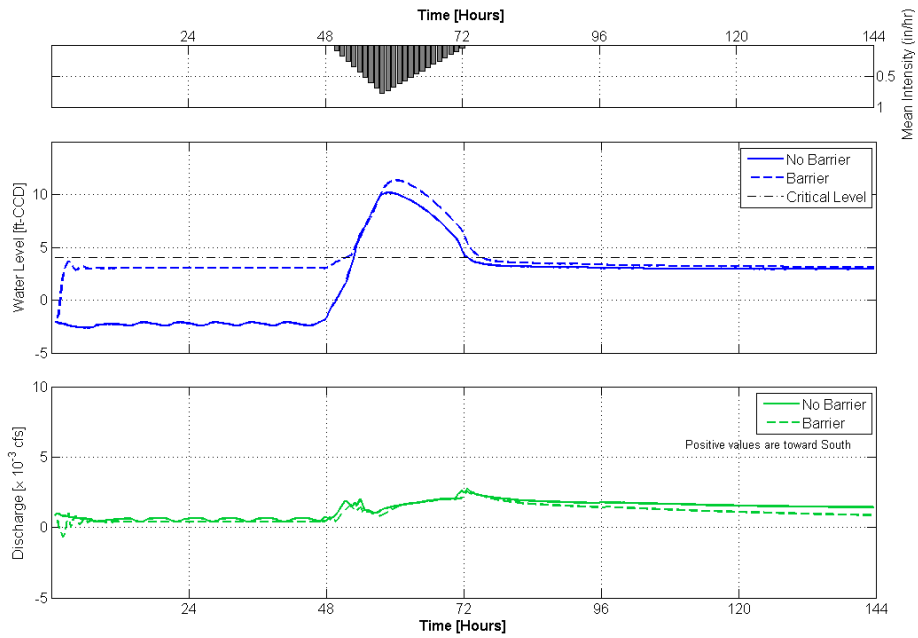


Figure 4.18: Effect of barrier at Lawrence Ave. / 500-year storm.
Lake Michigan=+3 CCD and Finite-TARP

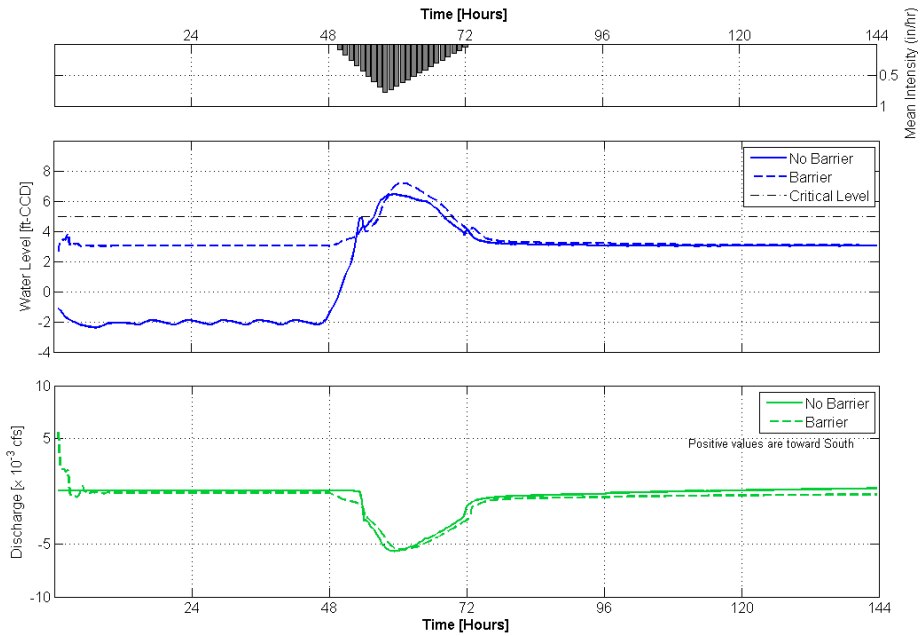


Figure 4.19: Effect of barrier at Wilmette PS / 500-year storm.
Lake Michigan=+3 CCD and Finite-TARP

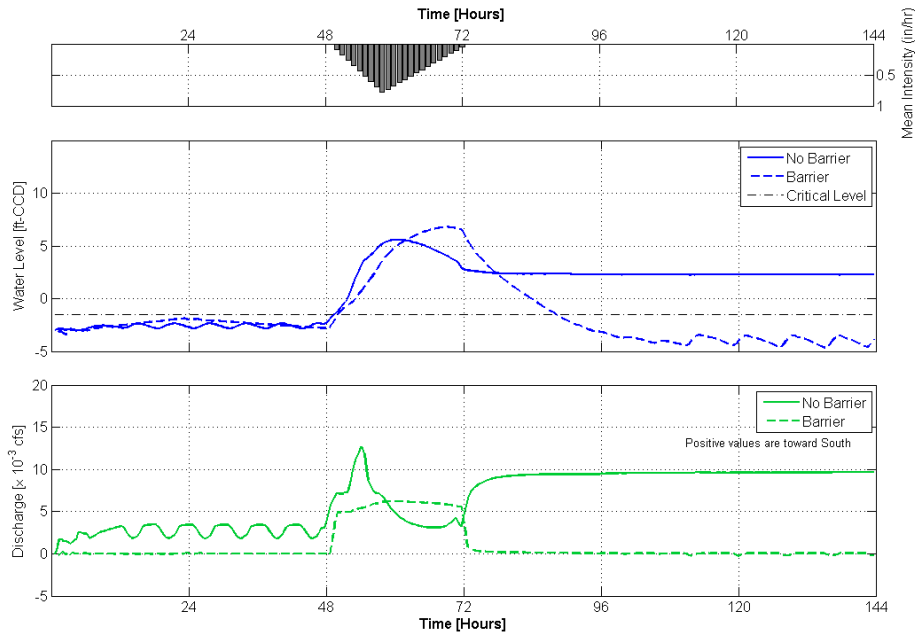


Figure 4.20: Effect of barrier at 31st & Western / 500-year storm.
 Lake Michigan=+3 CCD and Finite-TARP

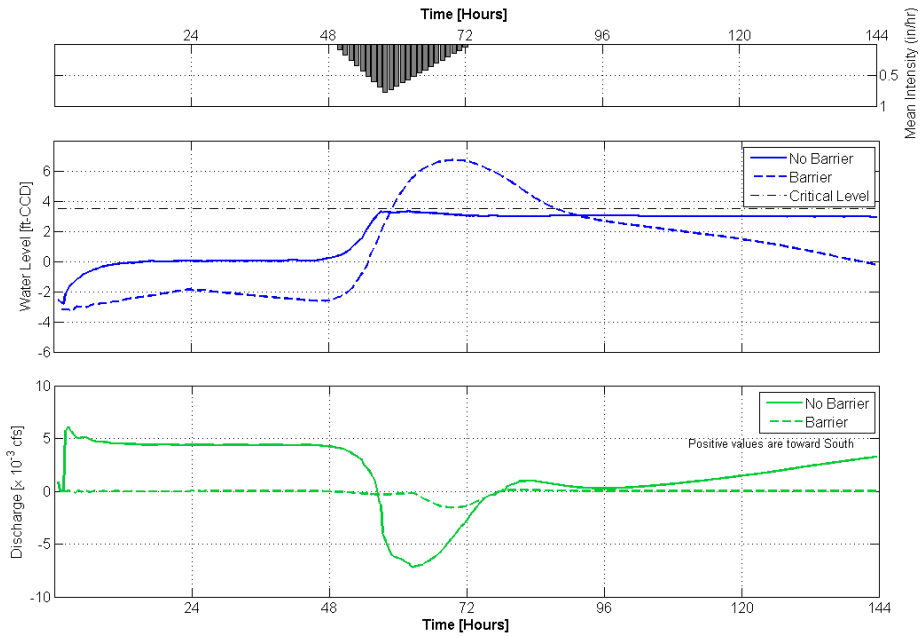


Figure 4.21: Effect of barrier at O'Brien Lock & Dam / 500-year storm
 Lake Michigan=+3 CCD and Finite-TARP

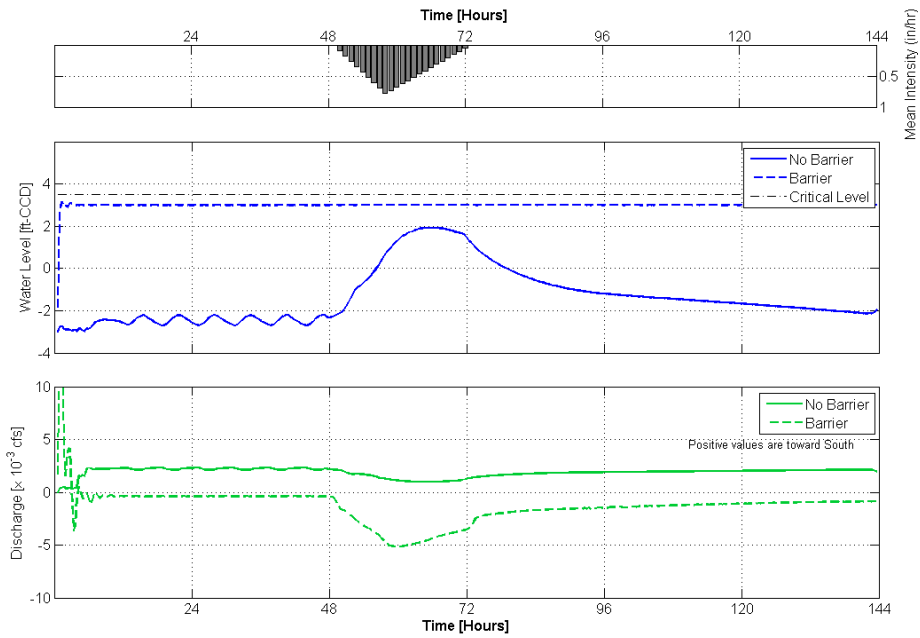


Figure 4.22: Effect of barrier at Columbus Dr. / 500-year storm
Lake Michigan=+3 CCD and Infinite-TARP

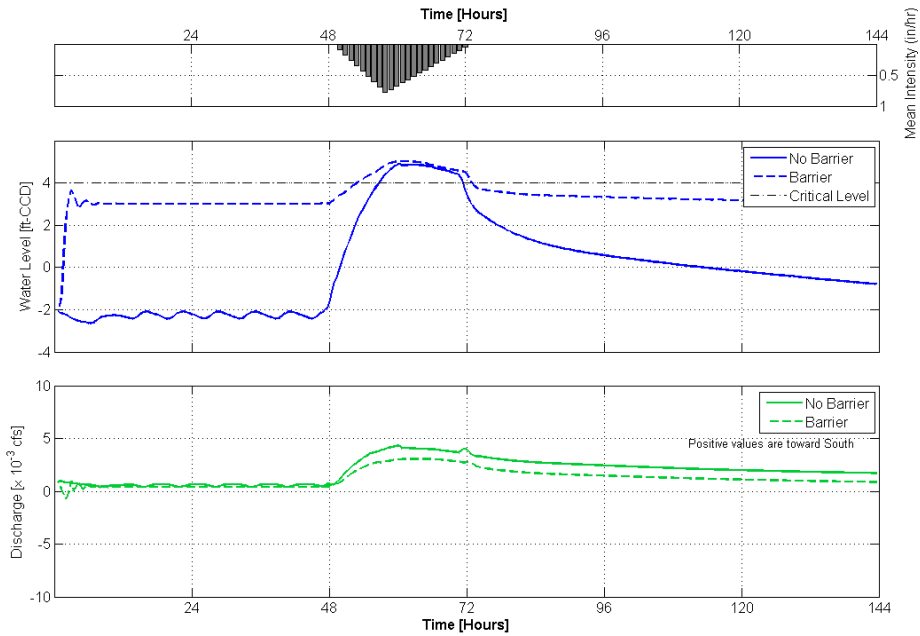


Figure 4.23: Effect of barrier at Lawrence Ave. / 500-year storm
Lake Michigan=+3 CCD and Infinite-TARP

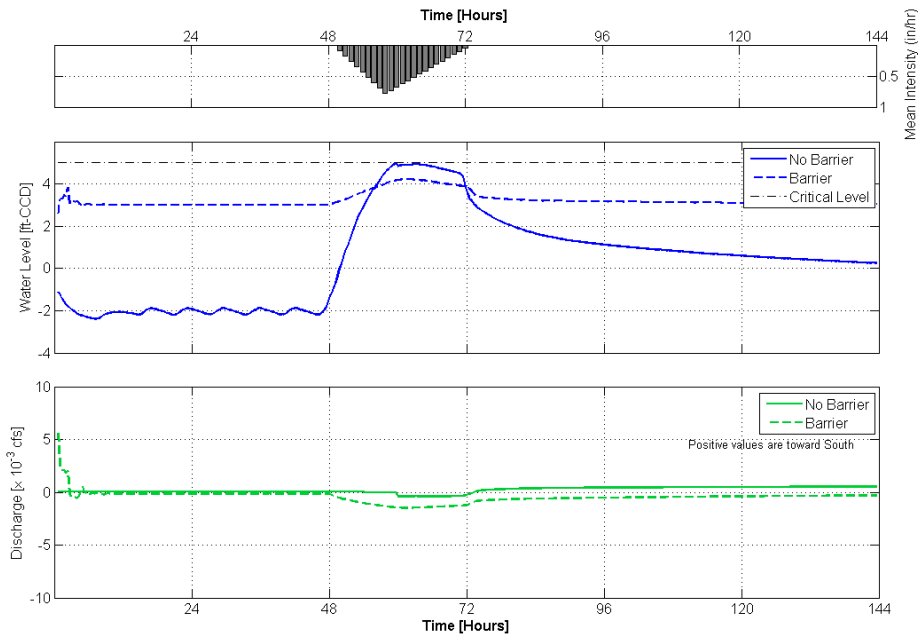


Figure 4.24: Effect of barrier at Wimette PS / 500-year storm
Lake Michigan=+3 CCD and Infinite-TARP

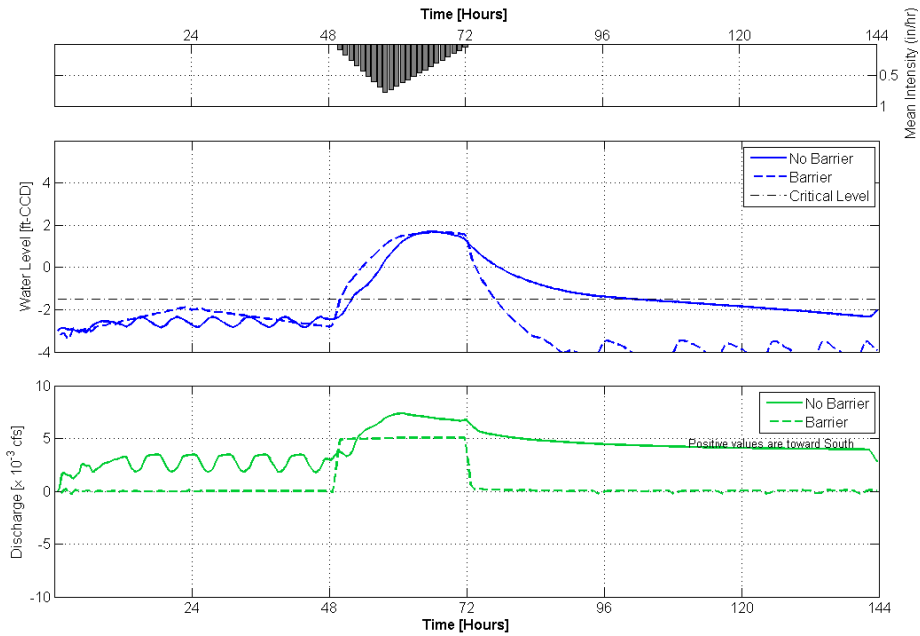


Figure 4.25: Effect of barrier at 31st & Western / 500-year storm
Lake Michigan=+3 CCD and Infinite-TARP

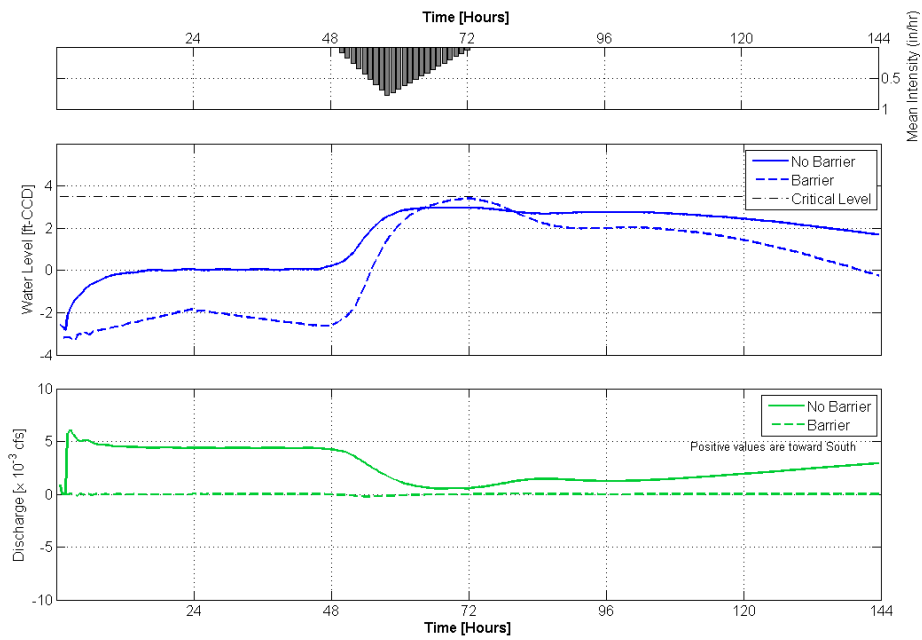


Figure 4.26: Effect of barrier at OBrien Lock & Dam / 500-year storm
Lake Michigan=+3 CCD and Infinite-TARP

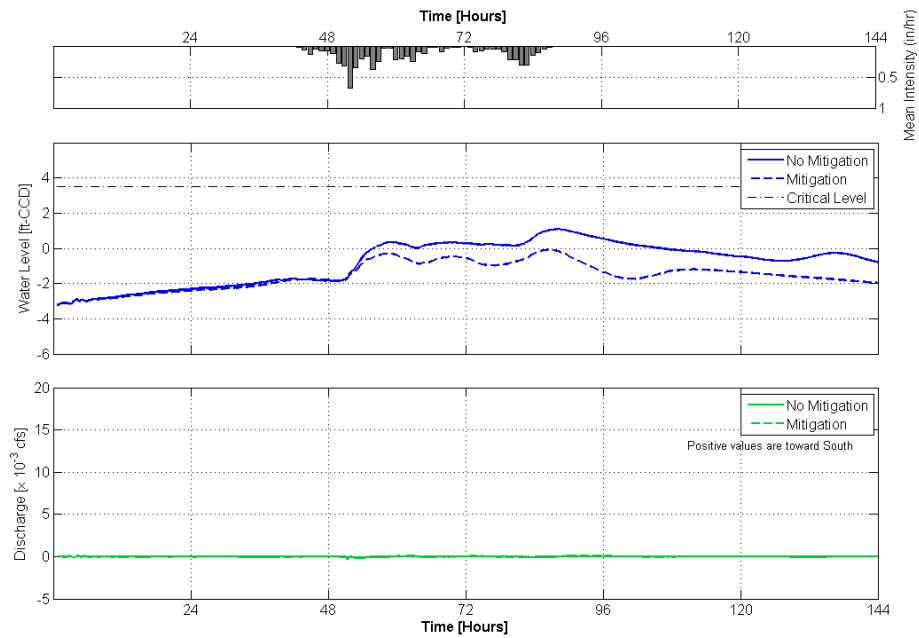


Figure 4.27: Effects of mitigation works at OBrien Lock & Dam / 100-years storm

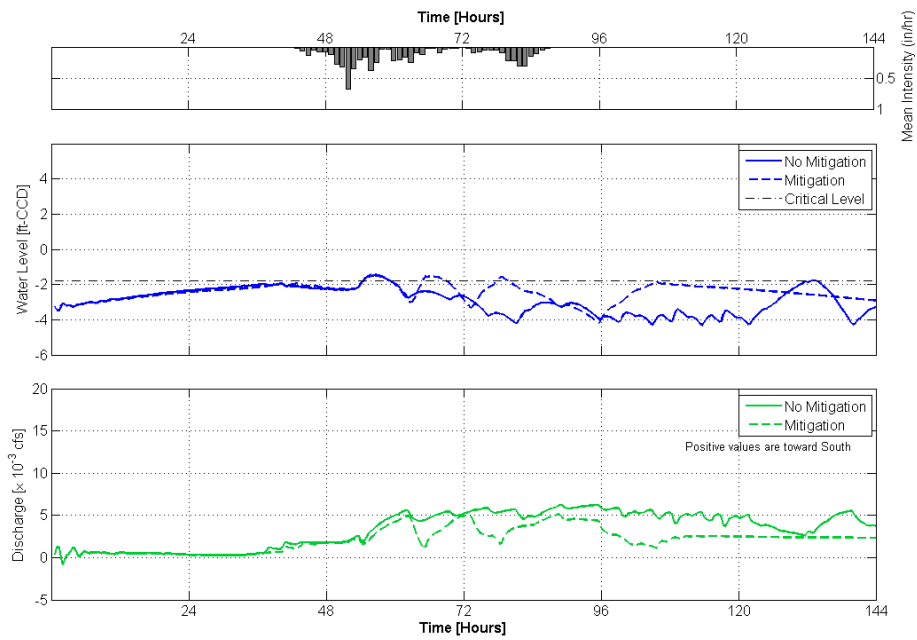


Figure 4.28: Effects of mitigation works at Sag-Junction /100-years storm

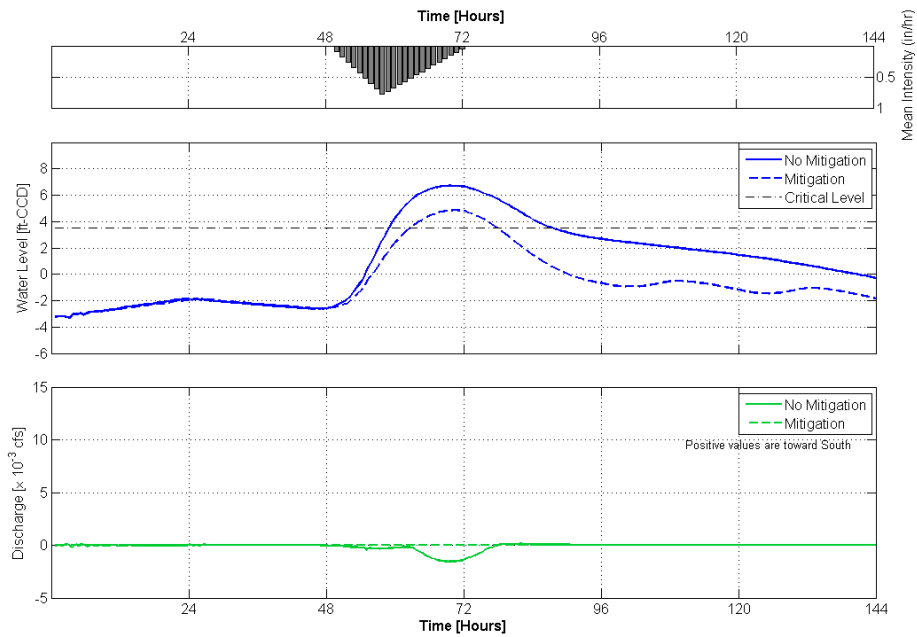


Figure 4.29: Effect of mitigation works at OBrien Lock & Dam / 500-years

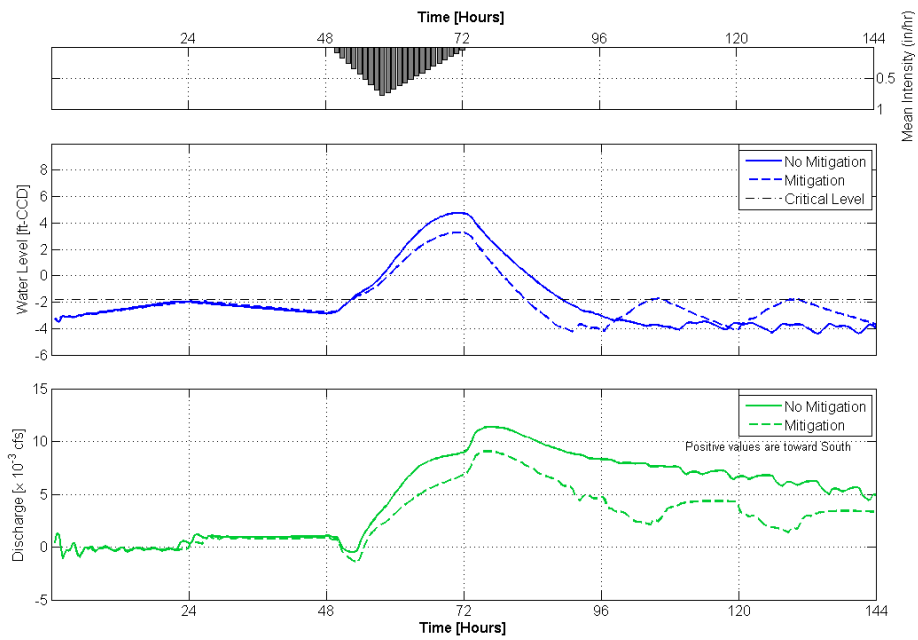


Figure 4.30: Effect of mitigation works at Cal-Sag Junction / 500-years

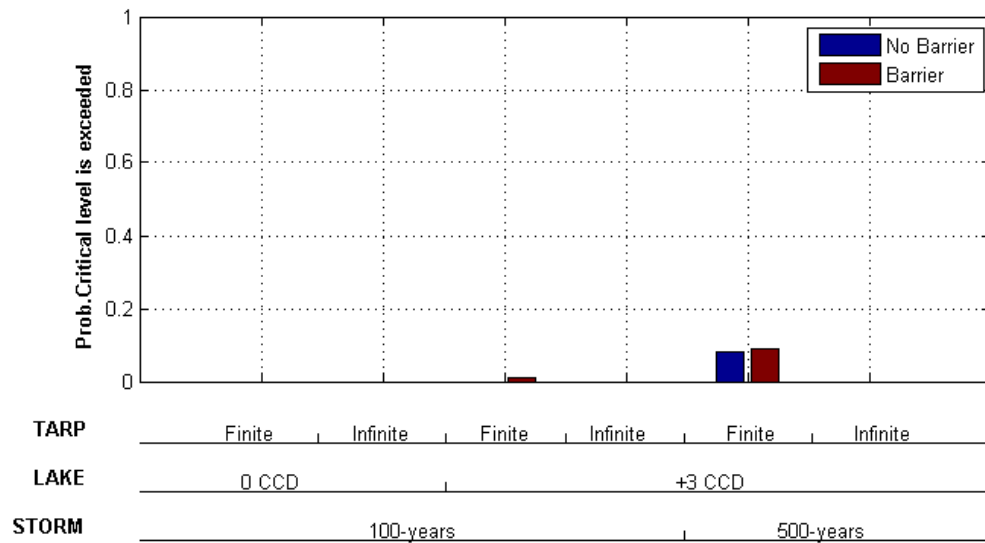


Figure 4.31: Fraction of time critical levels are exceeded at Wilmette PS

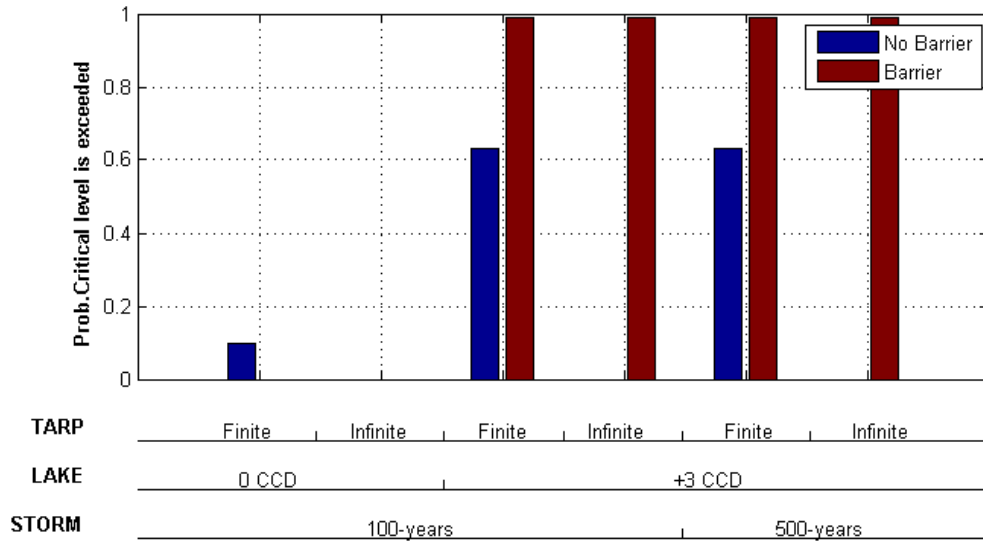


Figure 4.32: Fraction of time critical levels are exceeded at Roosevelt Rd.

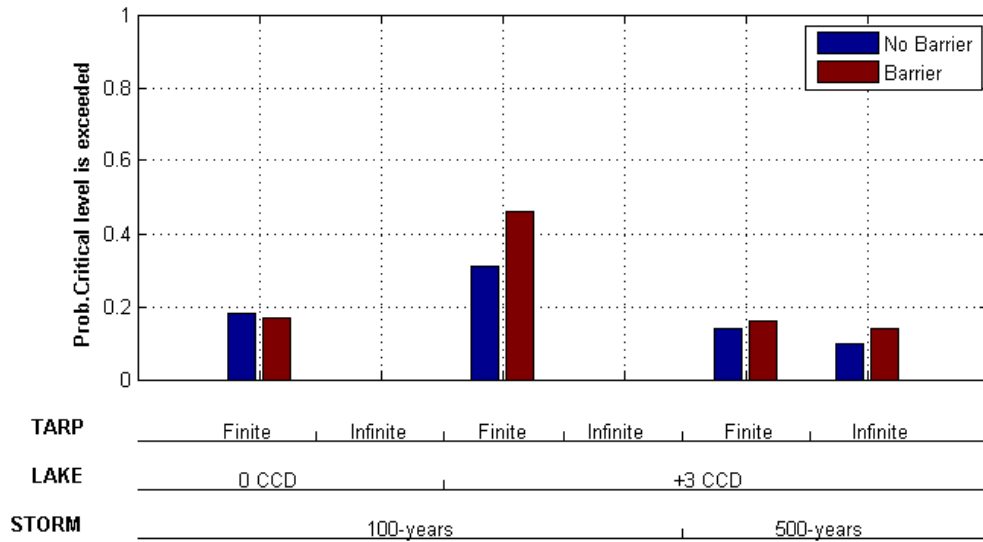


Figure 4.33: Fraction of time critical levels are exceeded at Lawrence Ave.

5 Findings

The effect of the barriers and the new operational paradigm (lakefront gates permanently fully open) do have important consequences on the water levels in CAWS and therefore on flooding in some areas of Chicago. This is particularly true for the north part of the system (North Shore Channel, North Branch, Mainstem, and South Branch) because the ability to controlling water levels in this portion of the system using Lockport would be lost on the lakeward side of CAWS with the South Branch Barrier.

Lake Michigan becomes a dominant factor in determining water level in CAWS with the barriers in place and the controlling works left open, particularly near the Wilmette Pumping Station and on the Mainstem Chicago River. If an extreme storm hits the City when Lake Michigan water levels are high (+3ft CCD) there would be a greater risk of basement flooding than for the current condition (no barriers), even for reduced flood-peak levels in CAWS. The reason is that flooding in Chicago is not necessarily caused by overbank levels in CAWS, but by sewer backups. This happens when high levels in CAWS close the tide gates at the CSO outfalls, so that water is unable to drain from the sewers. From the simulations results, the only area where overbank flows may occur during extreme rainfall events is by the confluence of North Branch, North Shore Channel, and Chicago River.

On the other hand, with Lake Michigan at average water levels (0ft CCD) the peak water level in CAWS near the lakefront (Columbus Dr.) are significantly lower with the barriers in place and the controlling works fully open than for current conditions (no barriers). Therefore, as explained above, there would be a lower chance of flooding Chicago by sewer backup. With Lake Michigan water levels at 0 CCD, water levels in CAWS are only lower without the barrier for the “dry” conditions, but this is not relevant for flooding of the City of Chicago.

A side effect of the barriers is that the volume of flow discharged to Lake Michigan would be increased because any CSOs and WRP effluents north of the barrier and inflows from the North Branch must be evacuated through the lakefront gates without the option to travel south through Lockport.

Flow discharges are reduced on the Lockport side of the barriers. In that case the upper reach of the Chicago Sanitary and Ship Canal (CSSC) would basically convey only CSOs from Racine Avenue Pumping Stations (RAPS) down to the Stickney WRP. On the Cal-Sag and Calumet River branch, the Little Calumet River is the most important inflow into CAWS. Because of the reduction of the discharge in CSSC, peak levels are lower at the Cal-Sag Junction and the Cal-Sag Channel has enough conveyance (“transport”) capacity for draining the water towards Lockport with no significant variations on maximum water levels by OBrien Lock & Dam, except for the 500-year storm with Finite-TARP, and lake level at +3ft CCD. Therefore, in general terms, flood risk in the south portion of the system is reduced in presence of the barriers.

The following are other findings on this study:

- When the barriers are in place and the gates are permanently open, Lake Michigan becomes the dominant factor on the water levels in CAWS in the downtown area and North Shore Channel. With high water levels in the Lake the barriers would keep CAWS higher during dry weather and pre-storm conditions than without the barriers. But, when Lake Michigan levels stays near historic average, water levels on the lakeside of CAWS would be lower than for current “ideal” conditions, and navigation would be impacted. This is because the regulation capacity of Lockport and the controlling works at the Lakefront would be lost with the barriers.
- Storage capacity of CAWS that allows for flow reversal minimization to Lake Michigan would be significantly reduced with barriers and new operation because the lakefront gates would remain open, thus subjecting the system to ambient water-level in Lake Michigan.
- On the Mainstem Chicago River (by Columbus Dr.) the peak flow would be reached earlier than for current conditions, because the water would flow straight to Lake Michigan instead of being partially stored in the canals. In case of flooding this means shorter response time for the City to respond to a flooding event.
- Water levels by the confluence of North Branch and North Shore Channel (by Lawrence Ave.) are strongly influenced by flows coming from the North Branch. At the same time, high levels at Lawrence Ave may have backwater effects on North Branch, thus reducing its draining capacity and increasing the risk of flooding due to backups through submerged pipes and/or by overbank flow in that area.
- Most of the CSOs are located on the lakeward side of the north barrier (Chicago River South Branch, North Branch, and Mainstem). Without the barriers these CSOs regularly flow southward through Lockport or would be stored in CAWS until the lakefront gates are opened, if necessary, to avoid overbank levels. In this manner reversal flows to Lake Michigan are minimized. However, with the barriers in place, most of the CSOs would be sent straight to Lake Michigan, mostly through the Mainstem Chicago River.
- On the south part of the system the barriers reduce the flow through the CSSC as most CSO would flow to Lake Michigan. By 31st & Western (Lockport side of barrier) the flow is basically limited to CSO discharges from RAPS (max. about 5,000 cfs). Other significant inflow is Stickney WRP (2,500 cfs). On the Calumet River, Little Calumet River is the most important inflow into CAWS. By the south barrier, on the Lockport side, critical levels are not strongly affected by the barriers, except for the condition 500-years, Finite-TARP (pre-filled tunnels condition), and high water levels at Lake Michigan (+3 CCD). In that case water level without the barrier is much higher, because of high flows from Little Calumet, and a reduced capacity of Cal-Sag Channel due to backwater effects by CSSC. Thus, for such extreme condition the barriers would alleviate in some manner the risk of flooding

- Close to the lakefront (Columbus Dr., Wilmette Pumping Station) the probability of exceeding critical levels (as defined by MWRDGC in its operation manual) is lower than for stations at inner locations (Lawrence Ave, Grand Ave, and Roosevelt Rd.), where probabilities are increased in presence of the barrier. Most significant increments are for the case 100-year storm, Finite-TARP, and lake level at +3 CCD at Lawrence Ave. (+15%), Roosevelt Rd. (+36%) and Grand Ave (+7%). These critical levels do not indicate overbank flow in CAWS, but were considered as a reference in this study as they define when flow reversals to Lake Michigan begin under current operation by MWRDGC.
- The effect of the mitigation works at Little Calumet River has little impact on flood-peak levels and discharges in the Cal-Sag Channel and CSSC for the 100-years storm event. Even without the mitigation work the flood control structures at Lockport have enough conveyance capacity to keep water levels below critical (as defined by MWRDGC) during the entire period at OBrien Lock & Dam, and most of the time at the Cal-Sag Junction (>95%).
- The mitigation works play a more important role on the 500-year storm event. The admissible (or critical) level at OBrien Lock & Dam is exceeded by 3 ft, about 20% of the time primarily due to flow coming from the Little Calumet River. By reducing the flow hydrograph by approximately 60% maximum admissible level (3.5 ft) will still be exceeded, but for a shorter period (10%).

Recommendations

- Estimates of CSO volumes and hydrographs discharge into CAWS would gain accuracy with a model that accounts for river stage and tide gate opening condition at outfalls.
- Better estimates of discharge coefficients at controlling works gates could be obtained with more sophisticated numerical or physical models that account for complex 3D flows in the vicinity of the gates.
- In order to avoid large variations on water levels during dry weather, operation rules of turbines and sluice gates at Lockport could be set to a goal or target level plus a small tolerance in monitoring locations. In this manner opening/closing gates would not be governed by maximum and minimum admissible water levels in the system all the time.
- The discharge capacity of controlling works at Lockport is affected to some extent by the conditions of Des Plaines River. A better understanding of the hydraulics on that matter would improve the estimate of discharge capacity at Lockport Controlling Works, a major flood-control feature in the CAWS.

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